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Automated System for Holographic Lightfield 3D Display Metrology (HL3DM)

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FINAL REPORT

THIS IS A SMALL BUSINESS INNOVATION RESEARCH (SBIR) PHASE I REPORT.

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14. ABSTRACT This SBIR Phase I report summarizes the investigation of an automated test system for the Field of Light Display (FoLD) class of 3D display systems. Types within the FoLD class include: lightfield, volumetric, holographic, and other systems capable of producing continuous parallax imagery viewable without special glasses. A literature search and test procedures are included. The typical set of tests provided within the report is based on the Society for Information Display (SID) International Display Metrology Standard (IDMS) Version 1 document and other new methods proposed herein. A review of available commercial systems guided the authors to propose the use of a high resolution photometric camera mounted on a robotic arm to perform a series of automated measurements.

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Field of Light Displays, FoLD, 3D Displays, Lightfield, Volumetric Holographic, Metrology, Automated Measurements, Photometry, Colorimetry

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1.0 SUMMARY

This final report summarizes the activity to find a set of methods and implementation to measure and characterize field of light displays (FoLD). It includes light-field displays, volumetric and holographic displays, and other multi-view 3D displays without eyewear.

We have based the work on the display standard IDMS1 [1] which covers testing procedures for spatially aligned stereoscopic displays spatially aligned (using eyewear), auto-stereoscopic displays (no eyewear) with horizontal parallax multiplexing (parallax barriers or lenticular lenses), and basic tests for light-field displays. We summarize the best procedures from this document [1] to include 2D luminance and color uniformity, 2D image contrast and 3D angular behavior. These important topics are affecting the image quality in general, and somewhat the depth effect quality of 3D images.

Stereoscopic displays are mostly based on the stereopsis effect, and has parallax in the horizontal direction. However, the FoLD have depth perception based not only on stereopsis with binocular disparity but also on additional cues, including convergence and motion parallax. In this case it is hard to measure the FoLD cross-talk between the eyes, and we will use high resolution tests to estimate the depth perception. The details are described.

For volumetric and holographic displays we proposed a method which is similar to range finding, or auto-focusing techniques of photography. These methods don't have ready tools, and we intend to build them with proper algorithms during the Phase II of this project.

We investigated several measurement tools to implement the above proposed methods. The most commonly used equipment today use mechanical stages and spot-photometers (or spectra-spot-photometers). In some cases the displays are mounted on a rotary stage or inside a dark closure. Since our display systems are varied, and relative big, we change the concept and would like to use robotic arm. This allows both front of display measurement as well as measurement from above a table top display (like the Zebra ZMD). The robot arm has the flexibility to move from front to top mode. We would like to include in our set-up a photometric camera. This allows small non-uniformity and local defects analysis. More considerations are summarized in this report.

The final testing system will perform a complete set of measurement sequentially once aligned to the display center point. It will compile a final report including analysis in predefined tables. A pass / fail criteria will be at each parameter measured.

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2.0 INTRODUCTION AND LITERATURE REVIEW

This report summarizes the development of test procedures and automated test system for light-field and volumetric displays, or in general field of light displays (FoLD). The report is based on the IDMS1 document [1]. However, the IDMS1 standard includes procedures for stereo displays (with eye-wear), and auto-stereoscopic displays (without eye-wear), but has limited procedures for light-field displays and no procedures for FoLD including volumetric displays. This report will start with the base measurements like stereo-uniformity, color and luminance uniformity, luminance and color differences between channels, cross-talk or extinction ratio, angular behavior and so on. It will then review literature regarding FoLDs, and propose the measurement procedures that should be included in an overall automated evaluation of FoLD displays.

2.1 3D Displays

The world around us is three-dimensional (3D). We are using the vision sense as the major sense to learn the world around us. Therefore making displays that are emulating the real world is important and challenging. The flat panel displays, which were developed and are manufactured these days in high volume are two dimensional and have some limitations to emulate the 3D world. They are around us in every aspect of life.

Most of the commercial 3D displays that are used today are based on the stereoscopic effect. They are using different technologies. Some are using eye-wear to separate the view of left/right eyes, and some are using optical means like parallax barriers or lenticular lenses to do this separation. In some cases the separation of the images presented to the eyes is simultaneous or fixed in time, and in some other cases it is sequentially modulated in time fast enough so that the eyes will not notice (> 50 msec) [2]. In all these cases the eyes are focused on a screen at a fixed distance, which might not be the proper distance as expected by the eye convergence angle of the displayed content. The displays based on the stereoscopic effect are called stereoscopic-displays (or in short: stereo-displays). For reference Figure 1 is the 3D displays map as presented in the IDMS1 document (Section 17, page 331).

While the IDMS1 [1] focused on the more commonly used stereo displays, we would like to focus in this work on the volumetric and holographic displays, as shown in the right side of Figure 1.

A very good overview of 3D displays is presented by Jason Geng [16]. We will not cover all the stereo display aspects, which are also covered by Abileah [3], and the methods for optical measurements. However, we would like to review a few of the 3D aspects of the human vision which will be later mentioned in the test procedures.

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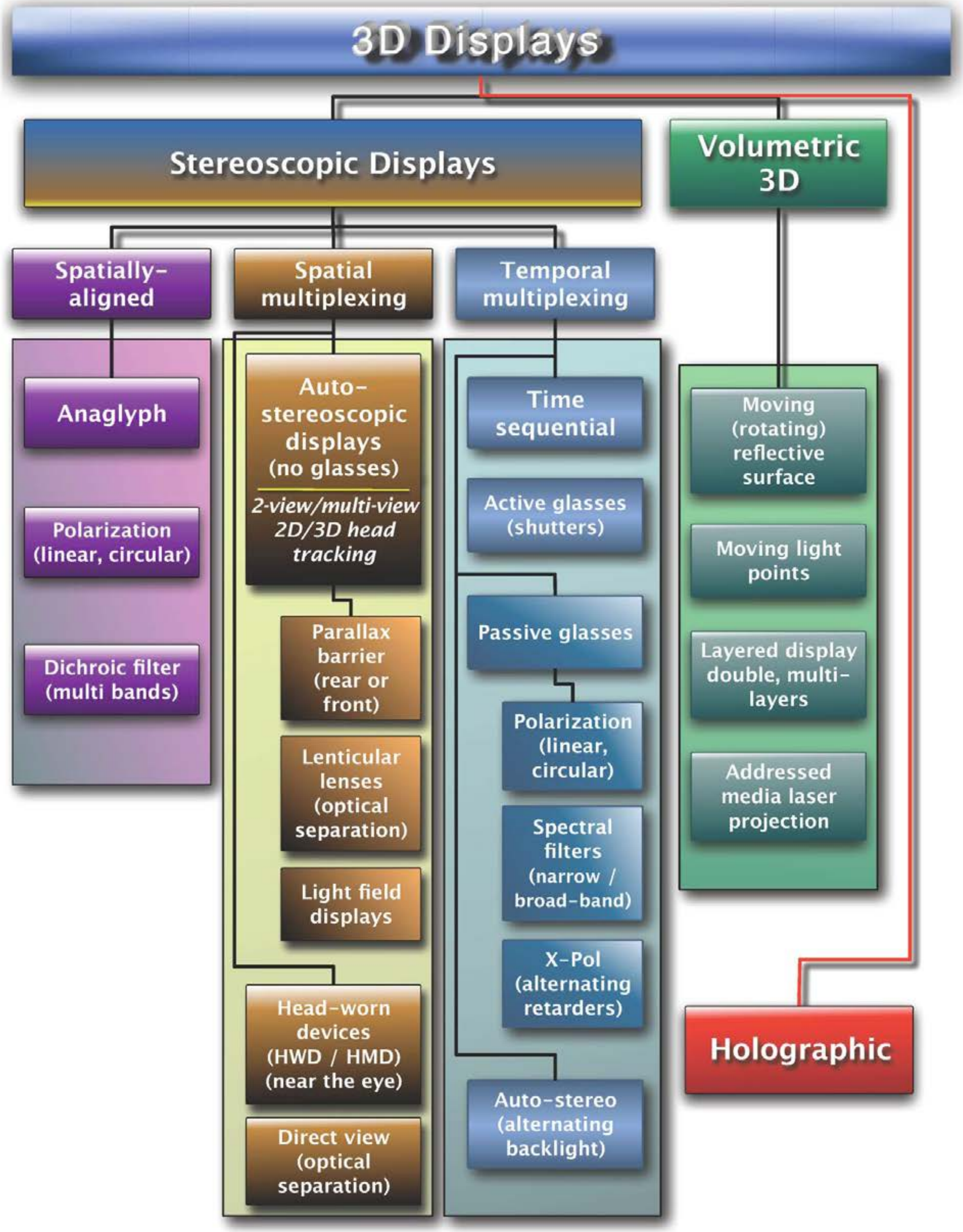

Figure 1. Types of 3D Displays (From IDMS1)

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2.2 Depth Cues

We are viewing the world with both eyes, and there are several cues that help us realize the 3D effects:

a. **Accommodation –** each eye is focusing on the objects and the amount of strain in the lens of the eye is a measure for distance to the object
b. **Convergence –** both eyes are fixed at the same object, but has to change orientation to meet this. The angle between the view directions of the eyes is the convergence angle. Closer objects will have bigger convergence angle
c. **Motion parallax –** moving the head will cause change in location of the objects. Closer objects will move faster. Farther objects will hardly move with the motion. (Some birds are moving their head all the time for this purpose.)
d. **Binocular disparity –** the images of the same object will be in a different position in each of the eyes, due to the viewing orientation. Closer objects will have bigger disparity (bigger difference in the images between left / right)

Not all these cues can be realized by the displays. The common problem with stereo displays is the accommodation. While we are looking at a flat panel display, it is at a fixed distance from our eyes. The images are expected to be at a different distance based on the convergence. Therefore with stereo displays the major problem is the accommodation-convergence conflict, which causes nausea when viewed for longer time. Howarth [11] shows a plot with the relation of the convergence and accommodation, and the comfort zone. It shows that stereo displays are limited in the range of convergence that they can put between 8 ~ 28 arc-min for a view distance of 1/3 m. This is applicable to a gaming display, or desk-top. Other effects that were studied by Kooi [9] shows that it is also important to have a low cross-talk to minimize eye-strain, and recommend to have 0.1% ~0.3% cross-talk in a stereo-display with at least 100:1 contrast and convergence of images up to 40 arc-min, in order to get good depth perception. These affects are important to stereo-displays. We assume that the volumetric and holographic displays will not have such problem, but will add this to the considerations when making measurements.

2.3 Two Dimensional (2D) Depth Cues

There are several 2D cues which are helping in the interpretation of images

a. **Linear perspective –** objects at a distance are viewed smaller, therefore when looking on a rectangle, it will looks as a trapezoid in oblique angle. Another example is rails of a train that look converging at the horizon.
b. **Occlusion –** One object is hiding partially another object. The brain interprets that the full object is in front of the partially hidden, and therefore one is closer and the other is further away.
c. **Shading –** the partial illumination of an object and shades next to it can give clues as to the relative location. Sometimes the shade area of one object is into the other one. Variations in luminance of the object give clues as to the surface behavior.
d. **Texture –** the small features on the object surface**,** can help much to interpret the shape of the object, including the depth.

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e. **Prior knowledge –** of objects in different conditions, their motion behavior and typical illumination and shading when separated or in a group, can help much to interpret depth situations.

While all these 2D cues are helping when presenting 3D images in 2D displays, they are not sufficient to see the full 3D situations. They can reduced the eye-fatigue in some cases of conflicts. Geng [16] show a plot summarizing previous findings. The conclusion is that 2D cues, which he calls psychological depth cues, are not affected much by view distance. While the 3D cues, called physical depth cues, are affected much as a function of view distance.

2.4 Cross-Talk in Stereo Displays

As explained, in stereo displays, the two images presented to the viewer are slightly different to reflect the binocular disparity in real life. The object of images is also shifted horizontally to reflect the convergence. The assumption is that each eye is seeing a totally different images. However, most optical systems for stereo have some amount of leakage of information of one eye into the other eye. The ratio of unintended image to the intended information is the crosstalk. Woods [6] discusses in details the different definitions of crosstalk and the methods for calculations. Abileah [19] shows the methods that are used in the IDMS1 [1] document, and is summarized in these formulae:

Equation 1. $X_L = (L_{LKW} - L_{LKK}) / (L_{LKW} - L_{LKK})$

Where L is the measured luminance, sub-L is for the left eye, and KW means left image is black (K) and right image is white (W), and so on.

Similarly for the right eye we will have:

Equation 2. $X_R = (L_{RKW} - L_{RKK}) / (L_{RKW} - L_{RKK})$

These formulas will not be applicable to Light-Field or Holographic displays, since the separation of the images to the two eyes are not so clear for each view orientation.

Therefore we need a new technique to estimate the depth perception, which is not based on the stereo effect and its “purity” measured by the crosstalk. This will be discussed below.

2.5 Depth Perception and Resolution

In Light-Field displays, as well as volumetric and holographic displays, the images include the depth perception. Besides the stereo effect they include convergence and binocular disparity. However, this depth perception will not be visible if the resolution of the image is not adequate. Therefore people consider the resolution measurement as a metric for the quality of the 3D effect and depth perception. The measurement is done at a specified view distance from the display screen, which is the typical viewer location.

The resolution can be measured at one view distance for several depth values of presented information. For each depth value a sinusoidal pattern is displayed and the pattern is measured

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at the targeted view distance. Then we compare it to the reference pattern. This method is similar to the measurement of modulation transfer function (MTF). Getting the ratio of the measured pattern to the reference gives the MTF number. Repeating this tests at several image depth value and plotting the MTF for each, will give us a way to measure the depth perception. This method is described in the IDMS1 [1] Section 17.5.4 and is based on several papers cited there [20, 21, 22]. More detailed description and instructions will be described below.

The logic behind this test for Light-field, Volumetric and Holographic displays is that the image pairs are continuous, and the image per eye is separated from the neighboring image by the eye relief defined by the iris. In medium light levels the iris will have about 5 mm aperture. This is the area where the image should fall and it should be without mixing with unintended information from neighboring image. In the high resolution FoLD the separation will also be good and therefore the depth perception will improve.

2.6 Light-Field Displays

Light-field displays are based on the optical principle that instead of focusing the images to each eye separately at a given distance, the light beams emanating from the display are parallel beams and your eyes can view only the beams that are directed to them. The selection of beams will depend in space by the distance between the eyes (IPD - interpupillary distance). Figure 2 illustrates this graphically [1]. In both cases in this example a lenticular lenses are used and the plots are two dimensional (2D) cross section. This principle can be extended to multiple lenses and similar behavior in three dimensions (3D). For an autostereoscopic imaging a 2D lenticular-lenses should be adequate. In the light-field display the same pixels will show up to one eye as you move around (left – right). The condition that has to be met is that the eye interpupillary distance IPD will be maintained and match the pixels separation. Therefore in this case (and also in the multi-view case) it is important to have a very high resolution display with enough pixels and separation between them.

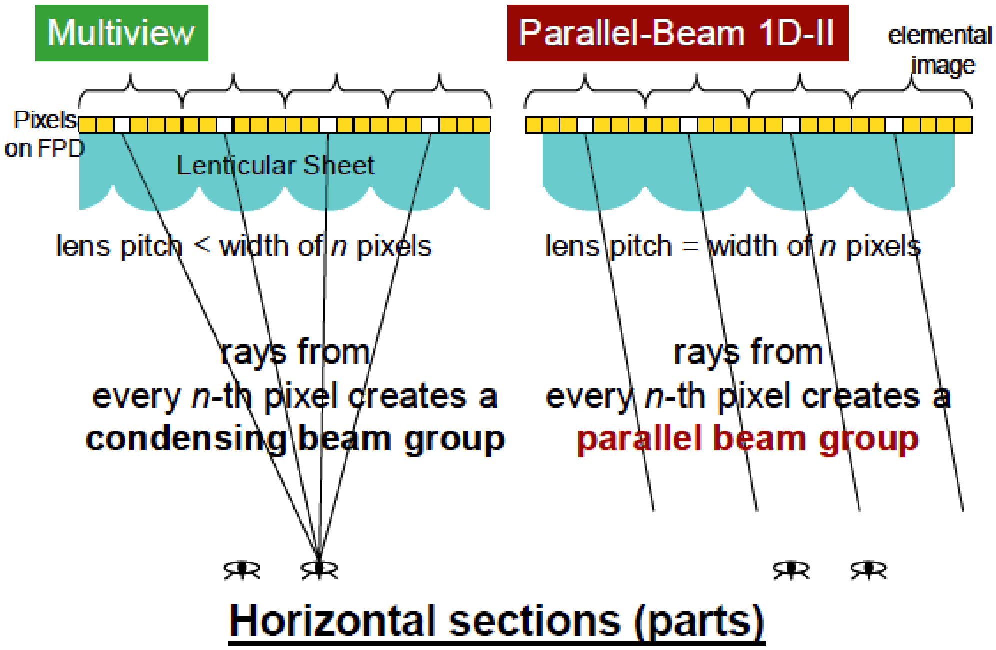

Figure 2. Comparison of Multi-View and Light-Field Displays

2.7 General Background for Light-field

2.7.1 Description. Light rays that are traveling in space, will hit a surface. This surface can be for example an array of lenses. Figure 3 shows examples of rays that are hitting two types of surfaces:

(a) Diffused surface (left side), which is scattering the rays to several directions – this generates a 2D image, and

(b) Clear surface (on the right), which transfer the rays without change – this generates 3D image, since we look on the origin of the rays, including their depth.

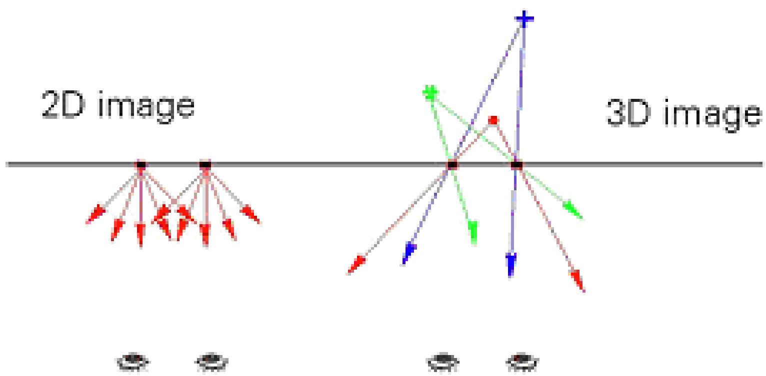

Figure 3. Rays Hitting Two Types of Surfaces: (a) 2D Image (diffuse), (b) 3D Image Redirecting (Clear)

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In order to trace back the rays, we have to put notation:

(a) The hitting location on the surface (x, y)
(b) The orientation of the rays emanating from the screen (θ, φ)

Therefore we can describe the surface of light field as:

F(x, y, θ, φ) – function that describes the surface with all its rays coming from each point and their directions.

The rays are described as example in Figure 4.

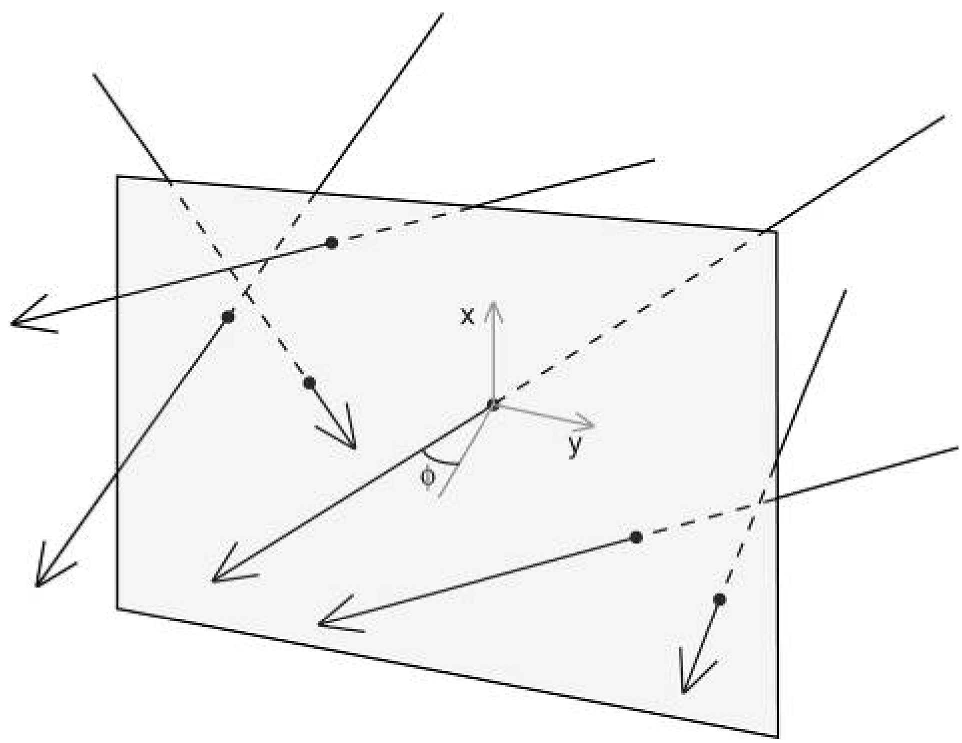

Figure 4. Light-Field of Rays Coming Out of a Surface, Each Ray from Different Location and Has Different Orientation

This notation is taken from the introduction by Kovacs in the IDMS1 [1].

2.7.2 The Plenoptic Function. Similarly to the notation above, a light-field can be described by the Plenoptic function for each ray. This is described by Jason Geng [16] as a function of:

(a) The location from which the light is emanating (x, y, z) – in space
(b) The orientation of the ray (θ, φ) – polar coordinates
(c) The wavelength of the light (λ)
(d) The time of observation (t)

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Therefore the Plenoptic function is: P($x, y, z, \theta, \varphi, \lambda, t$)

2.7.3 Effect on Measurements. The ray tracing described above show that there might be a difference in measurement techniques between multi-view displays and Light-field displays. This is described by Koike [5] as differences in ray space. This paper explains that the multi-view displays can be measured at close proximity with a Fourier Camera (e.g. VCMaster by Eldim, a conoscopic camera). This will give the luminance reading at the proper angles, since the rays are emanating in all directions and can be measured at the sweet spots, and in between. For light-field display it will not work, since the single ray direction will appear as single point and will not give a complete picture. Therefore they recommend using high resolution camera and method similar to modulation transfer function (MTF) measurement. The same team of this paper also wrote the section in the IDMS1 [1] that describes the MTF measurement. A more detailed procedure will follow in this document. Therefore for Lightfield displays and any other Field of Light Displays (FoLD) we propose to use a high resolution camera, since all of them have similar space of rays as defined by Koike [5].

We have to mention that in the Lightfield display with lenslets, there is a possibility to take the angular distribution of the rays coming from a single lens, using the conoscopic camera at close proximity and aligned carefully with the center of the lens. This is very complex, but can be done. This will give part of the space of rays map for the display for evaluation.

2.8 Instruments for Measurements

The measurement devices that will be used for the special tests for FoLD, are similar to the ones defined in the IDMS1 [1] section §3.1 (page 21), and are specified below:

2.8.1 Luminance Spot-Photometer.

(a) Should have optics that focuses on the display, and has defined aperture angle (e.g. 2°).
(b) Sensor spectra is optimized for photopeak measurements with 4% accuracy (or better).
(c) The repeatability should be 0.4% within 5 minutes.

2.8.2 Luminance Meter.

(a) Can be a sensor without focusing optics, like a pack. This is less convenient for the type of 3D displays that we are trying to measure, and most of the times impossible to use.
(b) The luminance meter should have photopeak corrected reading with 4% accuracy.
(c) The repeatability should be 0.4% within 5 minutes.

2.8.3 Color Photometer.

(a) It can be of one of the following types: spectra-spot-photometer, spot-photometer with color filters, or photometer without optics, but with color filters.
(b) The expanded uncertainty is defined in the IDMS1 [1] in appendix A1.1 (page 399), and should be $U_{col} < 0.005$, and repeatability of $\sigma_{col} < 0.002$.

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(c) For the type of displays that we intend to use the color meter for, it is mostly useful to have a spot-color-photometer that has focusing optics.

2.8.4 Array Detectors (Cameras).

(a) Photometric cameras will be the most useful instrument for the type of displays that we intend to measure.

(b) This includes cameras with multiple sensors array, of any of the commercial technology (CCD, CMOS, etc.). The sensors should be sensitive enough in the visible range and have photopeak filter correction.

(c) The cameras have focusing optics and have to be compensated for non-uniformity (both optical vignetting, and sensors non-uniformity).

(d) The number of pixels in the camera should be sufficient, and in most cases at least x3 higher than the phenomena to be measured, preferably x10.

(e) One of the main issues with cameras is the Moiré effect, and should be avoided by either change of view distance (effectively the pixels pitch) and the orientation (tilt angle).

(f) The IDMS1 specifies the accuracy of the camera to have relative uncertainty ULMD < 4%, and repeatability < 0.4 over 5 min. (see IDMS1 [1] page 21).

(g) Our intention is to use the cameras with color option, when applicable.

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3.0 TEST TYPES AND CATEGORIES

Testing the 3D displays will include three categories: (a) Visual inspection, (b) Basic display tests, and (c) depth measurements (focused in the next section).
The visual inspection is to make sure that all the functionality and alignments of the display are proper, before spending much time on characterization.
Basic display tests are part of the general behavior of the display, so that it will look proper. Most of these tests are based on the IDMS1 procedures [1] and will not all be detailed here, but just referenced with some comments. In the final report of this work, we will add the procedures in more details. The basic tests are detailed in the following paragraphs.

3.1 Basic Tests

In testing the 3D displays which are field of light displays (FoLD) we should include basic test procedures, as well as unique tests for FoLD. Among the basic tests are:

Luminance uniformity:
a. Local uniformity (including Mura)
b. Color uniformity
c. Color differences in small area
d. Contrast ratio
e. Angular luminance drop
f. Angular color shift
g. Temporal variations, like visible flicker
h. Video smearing
i. Artifacts – visible

For all these basic features are already established test procedures, most of them are summarized in the IDMS1 document [1].

In this section we will review some of them, and recommend our choice of procedure for this project.

3.2 Test Patterns

In order to perform several tests, we would like to use test patterns.
The IDMS1 [1] specifies several patterns which are described in Section 17.6.1 (page 381). However, since the focus of that section is on stereoscopic displays, the patterns include stereo pairs for left / right eyes.

3.2.1 Full Field Patterns Notation. For FoLD we don't have the need for image pairs. However we would like to define uniform fields at several depths. We will use the following notation:
(a) $\mathbf{W_{00}}$ **=** Full white field at depth zero
(b) $\mathbf{W}_{\pm XX}$ = Full white field at depth xx (which can be positive or negative)
(c) $\mathbf{K_{oo}}$ = Full black field at depth zero
(d) $\mathbf{K}_{\pm XX}$ = Full black field at depth xx (which can be positive or negative)

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3.2.2 General notation for full field patterns. For color displays we will have similarly the notation with Red (R), Green (G) and Blue (B)

(a) $\mathbf{Z}_{\pm XX}$ = Full field for Z color (Z = R, G, B, W, K, or other colors and mid gray levels) at depth ±XX (mm) (positive or negative relative to the display level)

3.3 Visual Inspection

Before performing a large set of measurements, it is recommended to put some test patterns and view the display for functionality and integrity.

The images should include depth elements. Figures for stereo-displays are in the IDMS1 [1] document, and include three types of patterns: (a) alignment tools, (b) visual inspection, and (c) patterns for measurements.

3.3.1 Types of Patterns to be used with Visual Inspection. For FoLD we would like to use also a set of images and patterns:

(a) **Alignment tools** - The alignment tools can help during adjustment of the display system, but also can help in visual inspection, and verification that the system is "behaving".

(b) **Typical images for visual inspection, proposed by Holografika** - The typical visual patterns can vary from display to display. However, all should include depth perception. The pattern presented in Addi A is a rotating structure and also move around with different depths. It covers significant situations and can be viewed from several directions.

Lee et al [24] are using the visual presentation for a real depth measurement. They put a triangle and a circle in different depths and let the viewer decide which pattern is in focus. The depth difference between the patterns is controlled by the simulation program. This could be a nice and quick way of measuring depth in FoLDs, but does not give an accurate metric.

(c) **Measurement Test patterns -** The test patterns for measurements can also help by looking on them visually. Sweeping through them can show if there are issues, like missing sections of the image, gross non-uniformity, or other problems.

3.4 Luminance Uniformity

There are two major methods to measure uniformity of a display:

a. Sampled Uniformity - Measure 5, or 9 points across the display, and

b. Area Uniformity - Capture the display image in a digital camera

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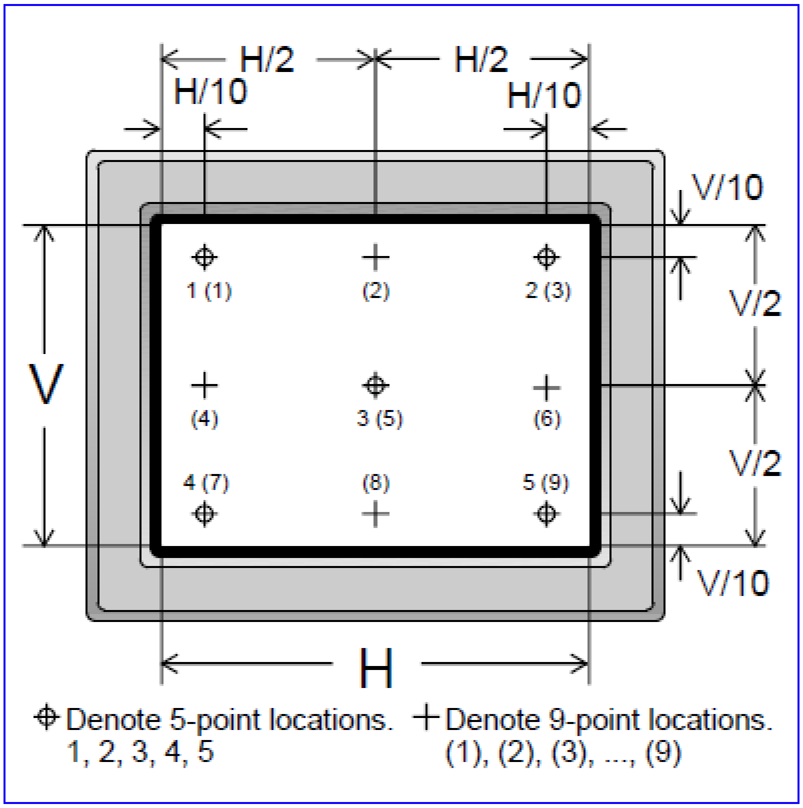

Figure 5. Uniformity Spot Measurement Locations (5, or 9 Points)

3.4.1 Sampled Uniformity. In the single point measurement, the spot-photometer is focused on the 5 or 9 points marked in Figure 5, and record the luminance numbers.
The photometer can move from point to point in two ways:

(a) Normal View - On a parallel surface, so that it is always normal to the display surface, or
(b) Vintage point - positioned in a vintage point (mostly normal to the center) and pointing to the measured point at oblique angle;

In all cases aiming at the 5 or 9 points on the display surface as in Figure 5.
Both types of measurements are described in the IDMS1 document [1] in Section 8 (page 134 and on).
These methods of single point measurements are called sampled uniformity. They can be weighted with emphasize to the center or other location, or just averaged and look for deviation.

3.4.2 Area Uniformity. The full area uniformity is done with a scanning array, or preferably with a high resolution and high quality camera. In this case the whole area is viewed and the luminance is recorded. The details of capturing and analyzing the data are in Section 8.2 (page 142) of the IDMS1 [1].

The IDMS1 is requiring to have an imaging colorimeter with:

(a) Resolution of at least 50% of the display resolution

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(b) Measurement done at a distance of 2570 times the pixels pitch (explanation are in the procedures at IDMS1 – Section 8.2, page 142)

See more comments at Section 2.7.1.4., above.

Once the image of luminance is captures, the information is processed using image processing tools. The procedures include:

(1) Rotate the image to match the orientation of the camera versus the display
(2) Crop the image to eliminate edge effects, and match to the edge of the active area
(3) moiré effect – can be mitigated by one of these steps:
    a. Defocus the optics
    b. Apply low pass filter in the Fourier domain
    c. Tilt the camera slightly

The data can be presented by the image processing tools, generate cross sections, and do histograms and other statistical analysis.
Area uniformity is taking the maximum location, versus minimum luminance and calculate the non-uniformity.

3.5 Small Area Uniformity

Using a camera to measure the luminance, gives also local variations of the luminance. With proper analysis of the luminance uniformity we can find out also any blotches or other local artifacts (Mura) that are visible and will show a bad looking display.

The Mura analysis we can be seen in the IDMS1 section 8.2.3 (Page 146). The image is first going a down-sampling to reduce noise and small variations. Then the local variations are recorded, and explain in page 147.

The alternative is to do first smoothing algorithm as explained above (down-sampling) and then another filter which is effectively making first derivative. This is equivalent to measuring the luminance difference within a small distance on the screen.

3.6 Color Uniformity

Color uniformity can also be measured in one of the methods described above:

a. Sampled uniformity - with spot-photometer at 5 or 9 points, or
b. Area uniformity (using a camera).

Similarly to the luminance measurements, the sampled uniformity can be done either at normal to the display (for each point) or from a vintage point oblique to each point.

We would like to use the area uniformity as our preferred method. The color data per point can be measured together with the luminance data, though making it more efficient.
The color camera should have proper spectral corrections to meet the color accuracy.

The color area can be captured as described in the luminance uniformity section above. The data has to be analyzed similarly. A smoothing algorithm with a low pass filter should be done first.

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Then the algorithm should find any combination of two points and the color difference between them specified as:

Equation 3 - $\Delta u'v' = \text{sqrt}\ (\ (u'_1 - u'_2)\hat{}2 + (v'_1 - v'_2)\hat{}2\ )$

sqrt = square root
^2 = to the power of 2
(u'_1, v'_1) and *(u'_2, v'_2)* – are two points of color on the map

Using proper algorithm the system can identify the points with extreme difference of vector ($\Delta u'v'$) over the whole color map.

The color unformity is equivalent to the uniformity, meaning that the differences are measured at any two points across the whole screen.

3.7 Color Differences in Small Area

The color uniformity map measured with a camera allows us to make further analysis. We can compare the primary colors at each location, and though find the range and variations of color coordinates across the display, as well as within small distances.
This is very similar to small area uniformity of luminance.
The reason for making this measurement is to make sure that we don't have high gradient of color changes across small area.

The analysis is done based on the color maps, as described above. However, this adds the calculations within small distances. This can use the color map and finding the gradients using filters.

3.8 Contrast Ratio

The contrast ratio (CR) is the ratio of white field over black field. The higher the CR, the image quality will improve. A minimum of 100:1 ratio will be considered OK in most cases because the higher, the better.
In stereoscopic displays, the CR can be measured in each channel (each eye). Most stereo and Autostereoscopic displays will have similar CR in both channel.

In FoLD it is also very important to have high CR in order to improve the 3D effect.
The recommended method of using area luminance can be implemented similarly. This means that we would like to use a camera, measure the white field, the black field and take the ratio of the two maps.

The IDMS1 [1] is specifying both the sampled colors uniformity, and the area measurement (See section 8.1.3. page 141). In both cases the ratio is calculated and the values of the CR is reported. In the area CR map we get more information, and can calculate the minimum CR on the map, as well as local variations.

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3.9 Angular Luminance Drop

It is desirable to have a bright enough display. A drop in luminance over angles, means that we have less brightness. This is one facet of the problem. The more severe and noticeable is sections of the display view at angles while other closer to normal. This will have big differences while looking on both at the same time.
This topic is well covered in the IDMS1 (Section 9, pages: 150 and on).

Here are some comments:

For measuring angular behavior we have to see if one of the three options will match the display technology:

a. **Spot photometer on a rotating goniometric stage**. Spot photometer on the goniometer will be adequate for sampled viewing angles. This is a slow measurement and therefore will be enough to take few measurements over the angles. This method is flexible to be used with most of the 3D displays, including stereo and FoLD
b. **Conoscopic camera**. The conoscopic camera is very effective and gives the complete set of measurements in fast and accurate measurement. However, it will not work with displays that don't have access to their surface. In this category will be most of the FoLDs.
c. **A camera on a goniometric stage.** Spot photometer on the goniometer will be adequate for sampled viewing angles. This is a slow measurement and therefore will be enough to take few measurements over the angles. This method is flexible to be used with most of the 3D displays, including stereo and FoLD.

The conoscopic camera is very effective and gives the complete set of measurements in fast and accurate measurement. However, it will not work with displays that don't have access to their surface. In this category will be most of the FoLDs.

A camera mounted on a goniometer will give much information. However, we have to be very careful with extreme tilted angles. In each angle, the camera has to be corrected for the oblique view.

The recommendation for most types of displays, is to use the spot photometer.

3.10 Angular Color Shift

It is important to have displays that show minimal variation of color shift over angles. There are few reasons:

a. We don't want to lose color saturation over angles, which is mostly the case
b. While viewing a 3D display from a designed eye position, we sometimes see sections of the display at oblique angle, and some other at close to normal. If there is a significant change in color, it will show badly on a uniform color area.
c. Color mixing will be a problem over angles, since many times the change in the three primary colors is not the same for each color.

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Color change over angles will be measured in the same way as luminance over angles. This means, that it can be with one of the three methods:

a. Spot color photometer (or spectra-spot-photometer) mounted on a goniometric stage
b. Conoscopic camera with color filters for color measurements
c. Color camera mounted on the goniometric stage

The most convenient way to get all the angular behavior at once is the Conoscopic camera. However, this is not useful for several of the FoLDs since the Conoscopic camera need to be in close proximity (e.g. 2 mm) from the display surface. Therefore, our best choice of FoLD should be the spectra-spot-photometer on a goniometric stage. This is the most accurate tool, and assuming that just few representative angles is sufficient, it is also easy to do. This will be a sampling method, and the color shift will be measured in the center of the display (or other point of choice).

The procedures should follow Section 9 of the ICDM1 [1] and more specific section 9.1 where the recommendation is to measure four typical angles.

3.11 Temporal variations, visible flicker

Temporal measurements are important and include several aspects. We would like to focus on two major ones: (a) flicker, and (b) affects that reduce video quality.
Since this is a big topic and is covered well in the IDMS1 procedures, we will rely on this document and will not detail much here, except for some comments.

The flicker is a phenomena that might cause nausea if severe, therefore it is important to reduce it below the threshold frequency that the eye can distinguish and with minimal changes in luminance levels between image frames. It should be measured with a fast responding photometer or optical sensor, and analyzed in a signal storage device.
The procedures are defined in section 10.5 Flicker of the IDMS1 [1]. The method is to record the signals and analyze them in the Fourier domain where amplitudes (or flicker level) are plotted as a function of frequency. The highest level is reported. For typical light illumination, and frequencies that are above 24 frames per second, we would like the flicker to be below 5%.

These methods are general and should be applicable to any of the FoLD displays. It is most important to include them in the set of tests for displays that have scanning, for example, the Acuity 3D display.

3.12 Video Smearing

In 3D displays that are showing video images, it is important that there will be minimal smear of the images. This topic is also covered in Section 10 of the IDMS1 [1].

There are several phenomena affecting the smear. The most important one is the response time of the system, explained in IDMS1 Section 10.2. For example, a slow responding liquid crystal (LC) material will change the optical effects slowly between the frames. This will cause for a moving ball across the screen to have an unwanted trail, like a comet in the sky. We would like the response time as defined in that section to be below the frame time (<16.7 msec).

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Other phenomena that can affect the smear is latency of the display. We would like that after the frame the image will disappear fast, before writing new information.

As mentioned, this topic is covered well in the IDMS1 and we would like to follow the procedures that are there. They will be applicable to FoLDs.

3.13 Artifacts–Visible

This is a visual test, and should be done with uniform luminance field, like full white.
The viewer should position himself in a typical view location and record whether there are visible artifacts. Such are including the structure of the pixels, patterns (e.g. film-patterned-retarders), parallax barrier strips, lenticular lenses, lens array (as in Light-Field), or any other structural effects.

The eye is very sensitive to dominant frequencies, and therefore can identify the structure as long as it is within the limit of the sensitivity curve for the specific lighting conditions. In most cases the frequency limit is about 50 line pairs for degree as shown in few curves in Peter Barten's book about the sensitivity of the eye and the papers [25, 26, 27].
Since the sensitivity is a function of the luminance levels, and angular resolution, it should be done at the targeted view location(s), including view distance as short as the display was meant to be used.

More specific, for the Light-field displays, we would like that the size of the micro-lenses will be small enough that the eye will not distinguish it. This means that it will be around 0.3 mRad (1 arc-min). This is about 0.1 mm from 330 mm view distance. For other FoLDs this means that any structure on the display should be smaller than the eye ability to notice it.

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4.0 3D DEPTH METHODS

We discussed in Section 3.4 that the depth of stereo displays are mostly influenced by the crosstalk. For light-field and other Field of Light Displays (FoLD) there is no separation between left and right eye. The depth perception is coming from a separation to each eye by directional rays. Therefore this is mostly influenced by the resolution of the display, the ability to control the rays in space, and somewhat by the display contrast.

We would like to propose three steps of depth evaluation:
(a) Visual – using a typical image including depth (both behind and above the displays surface)
(b) Focus of computer generated images (Lee method [24])
(c) Resolution tests at several depth

4.1 Visual Assessment

As in other tests, a visual inspection is best to proceed before elaborated test. Each display technology will have some limitations. However, we can use a typical image for this purpose. The IDMS1 proposed a rotating rounded image and is presented in Appendix A. This will show if there is any depth perception in the display.

4.2 Computed Patterns

Lee et al [24] proposed to use a computer generated images (called Computational Integral Imaging reconstruction-CIIR) of a triangle and a circle shown side by side. They control the depth difference between the triangle and the circle. Then they change gradually the depth difference and position the images. The viewer has to specify which image is in focus, and which not. If there is big difference between focused and non-focus images it will indicate that there is good depth separation in the display. In the following image from Lee (Figure 6) we see that the triangle is blurry while the circle is mostly focused. In this case by computation, the difference between the patterns is 20 mm, and therefore this is resolvable in this system.

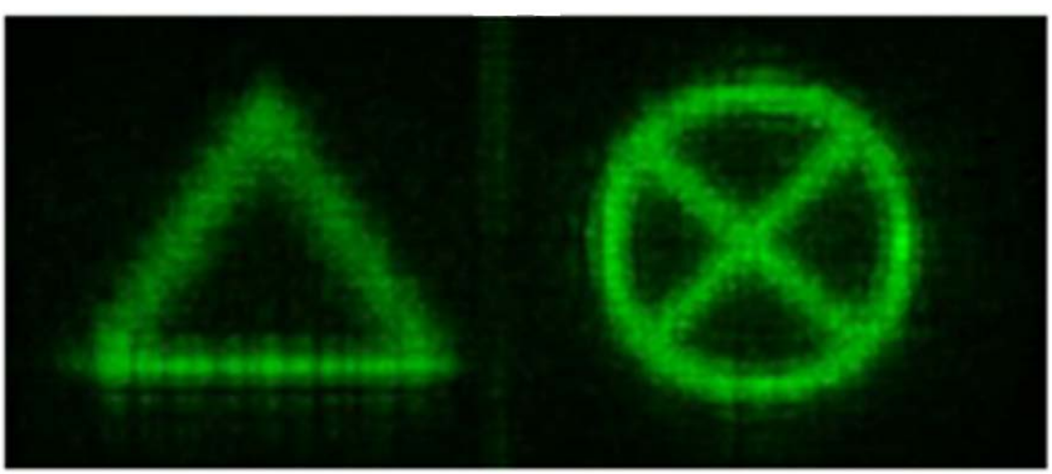

Figure 6. Triangle and Circle (from Lee's Paper)

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4.3 Depth Resolution Measurement

The method proposed by Koike [6] and is summarized in the IDMS1 [1] (section 17.5.4) refers to measurement of modulation transfer function (MTF) at a given depth.

The image presented on the display is a sinusoidal pattern with modulation in the horizontal direction, vertical, or diagonal. The image is designed at a specific depth, starting with zero depth at the display surface. The signal is viewed and measured by a high resolution camera, with pixels of at least x2 the number of pixels of the display. Preferably even x10 times as many pixels as in the display. Care should be taken to minimize Moiré effect, by either slightly defocus the lens, or small tilt of the camera (e.g. 5°).
Example of sinusoidal patterns are in Figure 7 taken from the IDMS1 [1] Section 17.5.4.

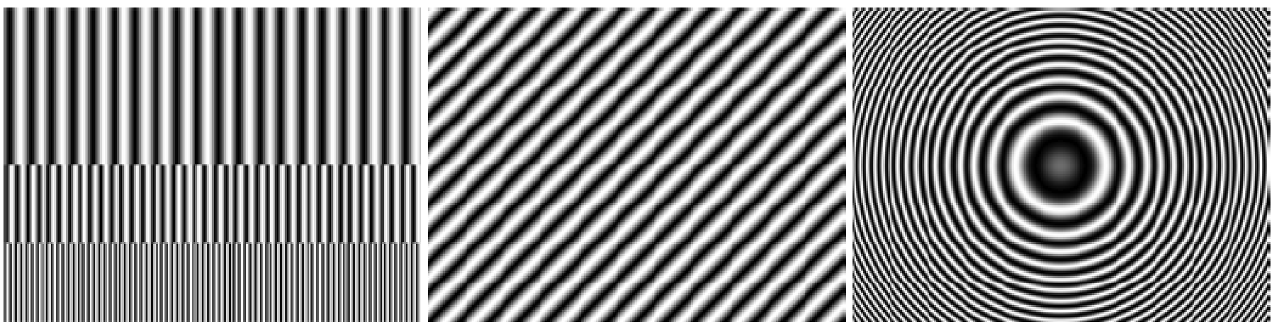

Figure 7. Example of Sinusoidal Patterns (Horizontal, Diagonal, Circular)

Once the image is captured, a horizontal (or vertical) cross section will be derived to get a signal over location curve. This signal will be divided by the input signal to get the relative modulation signal. The MTF will be calculated by taking the peak signal and divide by the valley signal. This will be done for several peaks and valleys and then averaged. Example of captured normalized curves for several depth are shown in Figure 8.

Note that the plots are normalized to the sinusoidal pattern and the horizontal axis is the depth (z) divided by the display diagonal dimension (D). It should be divided by the view distance (L), but this metric is more systematic and give similar results.

Once we have the 2D resolution from this analysis, we can use the ratio:

Equation 4 - $B_{2D} = B_{3D} * N = B_{3D} * (w / P_{ix})$

Where:

B_{3D} – is the resolution measured at a given depth (therefore it is 3D)
N – is the number of pixel along horizontal (or vertical)
w – is the display width (horizontal); or in the vertical will be (h)
P_{ix} – is the number of pixels along horizontal (or vertical)

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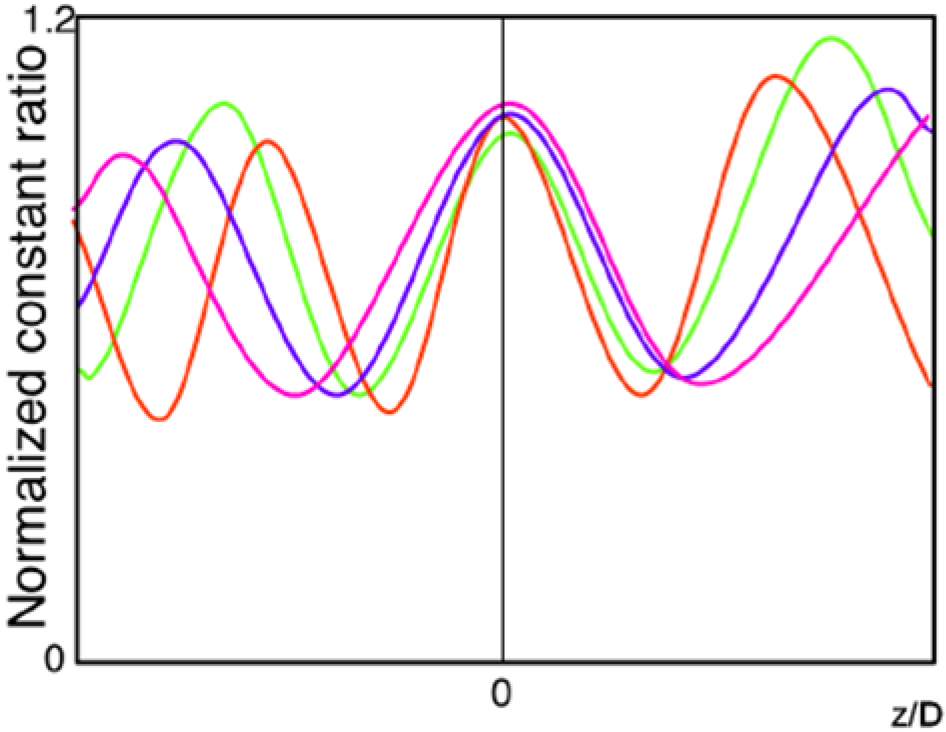

Figure 8. Normalized Sinusoidal Contrast Plots Captured in Few Depths

The meaning of equation 4 – is that we are calibrating the depth by using the horizontal (or vertical) display dimensions and number of pixels.

Recording this for a light-field display will give the depth resolution as shown in Figure 9, also taken from the IDMS1 [1] Section 17.5.4.

This plot is the normalized resolution by the lens steps in the vertical axis, and depth normalized by the display diagonal in the horizontal axis. As we see the resolution is best close to the display surface, where the depth z (or the ratio z/D) is close to zero.
This method is focused at the IDMS1 procedures for the Light-field displays, but is generic for any FoLD display. In other cases the MTF normalization will be the same. The depth (z) will be normalized by the view distance (L).

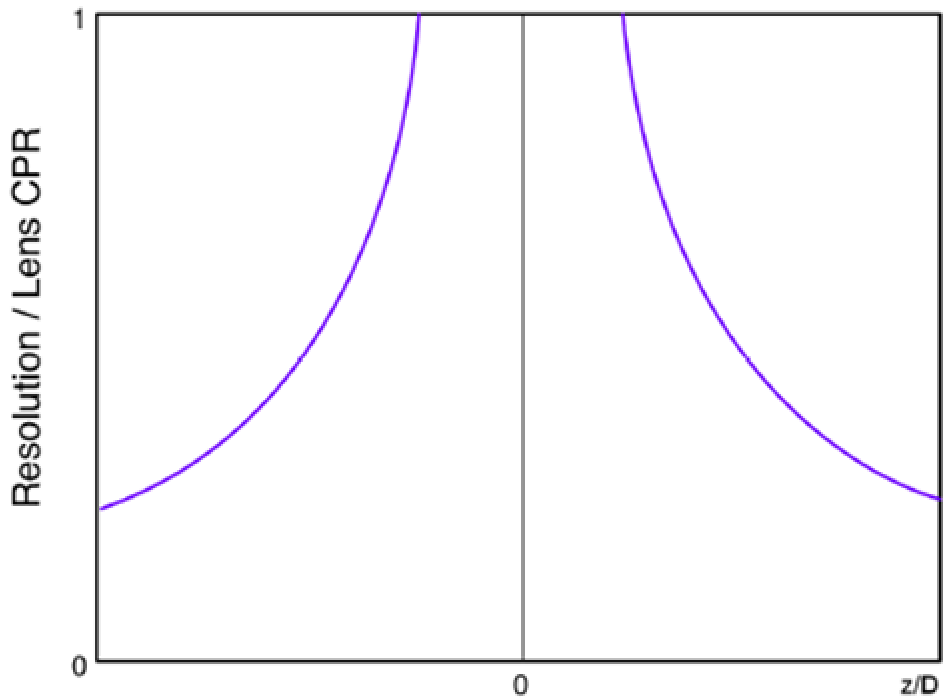

Figure 9. Example of the Resolution Limit versus Depth

5.0 SUMMARY – BASIC MEASUREMENTS

We have discussed the considerations and methods for measurements of field of light displays (FoLD). This report is based on the IDMS1 [1] standard and is meant to compliment it. The types of instruments for measurements are listed (see Section 2.8). We listed basic tests that are not unique to 3D, and discussed which methods will be best for testing FoLD. Table 1 lists the recommended tests and best equipment option to use.

Table 1. Basic Tests and Recommended Equipment

Test	Method	Recommended equipment	Comment & References
Luminance (Lum)	Spot measurement (center sample)	Spot-photometer	
Luminance uniformity	Area measurement	Camera (correction needed)	§3.4.2
Small area Lum uniformity	Area meas.	Camera (Mura analysis)	§3.5
Color uniformity	Area meas.	Color camera	§3.6
Small area color variations	Area meas.	Color camera (Δu'v' calculations)	§3.7
Contrast Ratio (CR)	Area meas.	Camera (W /K fields)	§3.8
Angular luminance drop	Spot measure at display center	Spot-photometer / goniometer	§3.9, at few angles
Angular color shift	Spot measure at display center	Spot-photometer / goniometer	§3.10, at few angles
Temporal variations, flicker	Fast sensor + signal capture	Fast spot-meter / signal processing	§3.11
Video smearing	Fast sensor + signal capture	Fast spot-meter /signal processing	§3.12
Artifacts - visible	visual	Use test patterns	§3.13

The unique measurement for 3D FoLD display is the depth. It is influenced much by the display resolution. As we see, we can estimate it by looking on a typical image with depth, estimate if by using computer generated patterns at two depths and assessing the focus of each image, or make full measurement of MTF at several depths.
In the following section we will generate a set of testing procedures based on the IDMS1 [1] basic tests listed in table 1, and based also on the reviewed papers.

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6.0 DETAILED TEST PROCEDURES

6.1 Basic Tests

As mentioned earlier, in testing the 3D displays which are field of light displays (FoLD) we should include basic test procedures, as well as unique tests for FoLD. We start with the basic tests, listed in Table 1. Here are the basic tests:

(a) Luminance uniformity
(b) Local uniformity (including Mura)
(c) Color uniformity
(d) Color differences in small area
(e) Contrast ratio
(f) Angular luminance drop
(g) Angular color shift
(h) Temporal variations, like visible flicker
(i) Video smearing
(j) Artifacts – visible

For these measurements are already established test procedures, most of them are summarized in the IDMS1 document [1]. Whereas in Section 4 above we had explanations of the different measurements, we would like to select from the IDMS1 specific procedures, and compliment them with more detailed instructions. In some cases, the IDMS1 gives several methods to choose from. We will do the selection for the case of 3D light-field displays, for volumetric, holographic and other FoLD displays.

6.2 Challenges

One of the major challenges specific for the FoLD is the focusing of the photometer or camera. In most of the stereoscopic displays the focusing is on the display surface. Lightfield and holographic displays have the image constructed "in the air" and therefore we will address this challenge in the following sections.

Angular measurements are also included. When using a camera we will have some sections of the image viewed closer to the camera, while others further away from the camera. We will address this issue as well.

6.3 Photometers

In the above section §3.7 (Instruments for measurement) we classified the photometers to few categories. We will repeat this here for completeness:
The measurement devices that will be used for the special tests for FoLD, are similar to the ones defined in the IDMS1 [1] section §3.1 (page 21), and are specified below:

6.3.1 Luminance Spot-Photometer.

(a) Should have optics that focuses on the display, and has defined aperture angle (e.g. 2°).

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(b) Sensor spectra are optimized for photopeak measurements with 4% accuracy (or better).
(c) The repeatability should be 0.4% within 5 minutes.

6.3.2 Luminance Meter.
(a) Can be a sensor without focusing optics, like a pack.
(b) This is less convenient for the type of 3D displays that we are trying to measure, and most of the times impossible to use.
(c) The luminance meter should have photopeak corrected reading with 4% accuracy.
(d) The repeatability should be 0.4% within 5 minutes

6.3.3 Color Photometer.
(a) It can be of one of the following types: spectra-spot-photometer, spot-photometer with color filters, or photometer without optics, but with color filters.
(b) The expanded uncertainty is defined in the IDMS1 [1] in appendix A1.1 (page 399), and should be $U_{col} < 0.005$, and repeatability of $\sigma_{col} < 0.002$.
(c) For the type of displays that we intend to use, making color measurements will be most convenient with a spot-color-photometer that has focusing optics.
(d) The spectra-spot-photometer will give the most accurate results.

6.3.4 Array Detectors (Cameras).
(a) Photometric cameras will be the most effective instrument for the type of displays that we intend to measure.
(b) This includes cameras with multiple sensors array, of any of the commercial technology (CCD, CMOS, etc.). The sensors should be sensitive enough in the visible range and have photopeak filter correction.
(c) The cameras have focusing optics and have to be compensated for non-uniformity (both optical vignetting, and sensor non-uniformity)
(d) The number of pixels in the camera should be sufficient, and in most cases at least x3 higher than the phenomena to be measured, preferably x10.
(e) One of the main issues with cameras is the Moiré effect. To mitigate this, we should either change the view distance (effectively the pixels pitch) and / or the orientation (tilt angle).
(f) The IDMS1 specifies the accuracy of the camera to have relative uncertainty ULMD < 4%, and repeatability < 0.4 over 5 min. (see IDMS1 [1] page 21).
(g) Our intention is to use the cameras with color option, when applicable.

6.4 Photometers Selection

For the basic measurements we will need a set of photometers according to their features. Table 2 is summarizing the different type of photometers split to Luminance and Color measurements.

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Table 2. Type of Photometers for Luminance and Color Measurements

LUMINANCE	COLOR
Spot-photometer – with focusing optics (view typical 1° ~ 2°)	**Spot-photometer – with focusing optics and color filters (View 1° ~ 2°)**
Spectra-spot-photometer – with focusing	**Spectra-spot-photometer – with focusing**
Contact luminance meter (pack)	**Contact luminance meter (pack) with color filters**
Luminance meter (Lux-meter)	
Camera (e.g. CCD)	**Camera (e.g. CCD) w. Colors**
Temporal luminance sensor – for response time and flicker tests	

For the set of measurements that are specified in the following sections, we would like to have the instruments that are highlighted in Table 2. To summarize:

6.4.1 Spectra-Spot-Photometer. Instrument with high dynamic range of luminance.

(a) For example the range of 0.1 cd/m^2 to 4000 cd/m^2 will be adequate.

(b) Reaching this range with an external neutral density (ND) filter installed on the lens is acceptable.

(c) In case that the dynamic range is limited, we might consider a separate spot-meter for luminance tests.

6.4.2 Photometric Camera. Camera with color capability and high resolution

(a) For resolution tests that intend to measure depth we need a camera with at least x3 pixels (preferably x10) compared to the display pixels, in each direction.

(b) For basic measurements of areal uniformity, and colors, it will be sufficient to have pixels which are only ½ to 1/10 of the number of display pixels in each direction. However, higher resolution camera (like in a.) will be fine to use.

(c) In case that the price of color camera with high resolution is very high we can compromise on:

- Lower resolution color camera (b.) and
- High resolution monochrome camera (a.)

6.4.3 Fast Response Sensor. Detector for temporal measurements.

(a) Fast response sensor with focusing optics

(b) Targeting flicker, response time, and other temporal measurements

(c) This sensor is actually a luminance meter, but fast responding. The output is recorded on a scope screen, or digitally.

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6.5 Flow Chart of Tests

Figure 10 shows a flow chart of the measurements. At the start of any set of measurements, we should align the luminance measure device (LMD) or colorimeter to the center of the display. More details are below. Then we follow with the visual inspection, the set of automated basic tests, and complete with the special tests, including depth measurement. At the end a report is generated with pass/fail criteria.

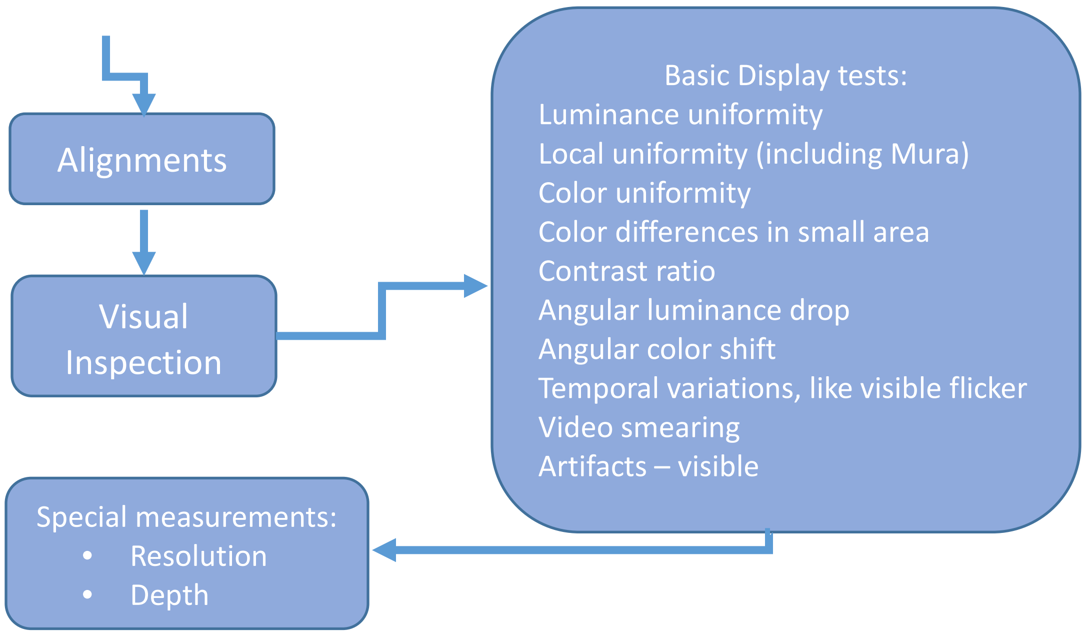

Figure 10. Flow Chart of Testing

6.6 Test Patterns

In order to perform several tests, we would like to use test patterns.
The IDMS1 [1] specifies several patterns which are described in Section 17.6.1 (page 381). However, since the focus of that section is on stereoscopic displays, the patterns include stereo pairs for left / right eyes.

6.6.1 Full Field Patterns Notation. For FoLD we don't have the need for image pairs. However we would like to define uniform fields at several depths. We will use the following notation:

(a) $\mathbf{FW_{00}}$ = Full white field at depth zero
(b) $\mathbf{FW_{\pm XX}}$ = Full white field at depth xx (which can be positive or negative)
(c) $\mathbf{FK_{oo}}$ = Full black field at depth zero
(d) $\mathbf{FK_{\pm XX}}$ = Full black field at depth xx (which can be positive or negative)

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6.6.2 General notation for full field patterns. For color displays we will have similarly the notation with Red (R), Green (G) and Blue (B).

(e) **$FZ_{\pm XX}$** = Full field for Z color (Z = R, G, B, W, K, or other colors and mid gray levels) at depth ±XX (mm) (positive or negative relative to the display level).

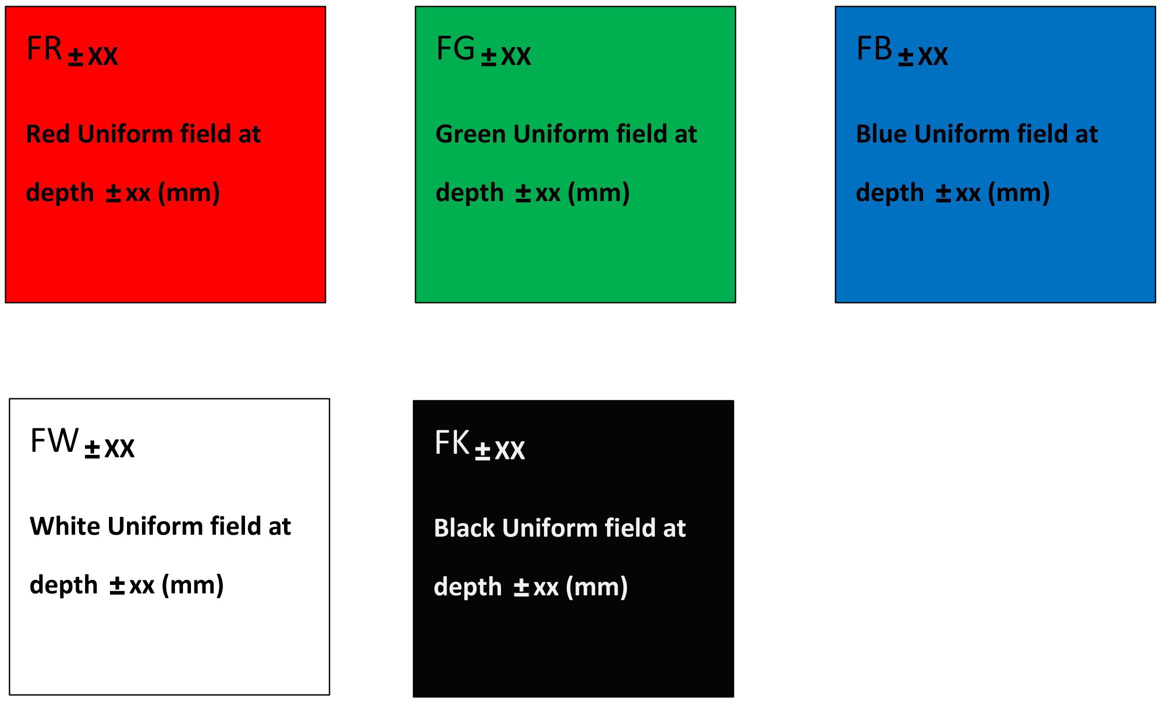

Figure 11. Full Field Uniform Primary Colors at Depth ±xx (mm)

This notation is similar to the IDMS1 [1], as defined in Appendix §A12 (page 446) except that we added the depth notation (example: FG ➔ $FG_{\pm xx}$)

6.6.3 Grid Patterns. Grid patterns are used to help focus the photometer or camera on a certain surface, as well as visual inspection that the system is linear.
The grid line pattern for 9 points uniformity tests are defined at the IDNMS1 [1] as *AT02P* pattern (see Appendix §A12; page 449).

Since we would like to have this pattern at several depths we will call them:
$GRID_{\pm xx}$ = GRID with 1/6 of width or height dimension for each grid line, at depth ±xx (mm) where positive xx is below the neutral depth and negative xx is closer to the viewer.

Figure 12 is showing the typical grid pattern with black lines on white background (K/W) and white lines on black background (W/K).

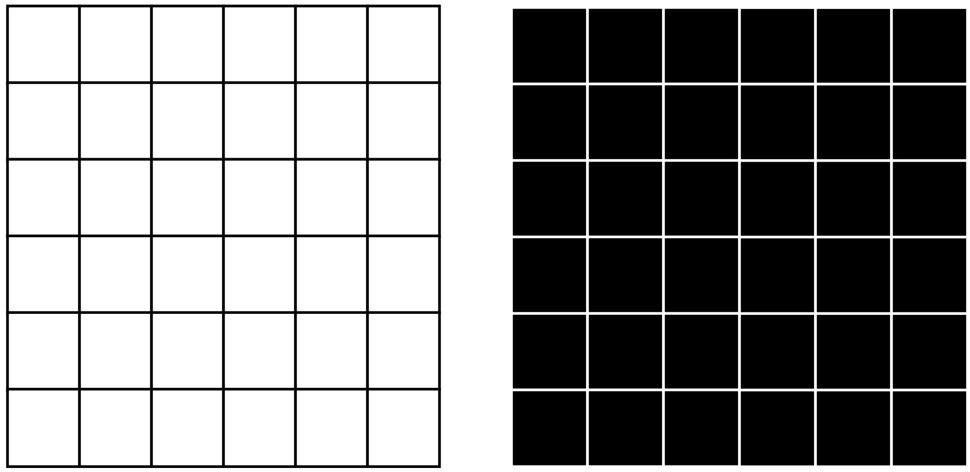

Figure 12. Grid Line Patterns (Fullscreen) Black on White (K/W) and White on Black (W/K)

6.6.4 Gray Levels Patterns. We would like to use two types of gray level patterns:

(a) Full field gray levels

(b) Patterned gray levels

The full field gray levels will look similarly to the white or black as in Figure 13, but the luminance levels will be mid-gray level.

We will follow the notation of the IDMS1 [1] as explained in Appendix §A12 (page 446), and will call gray level 127 as ***FS127*** (Full screen Scale 127 out of 256 gray levels).

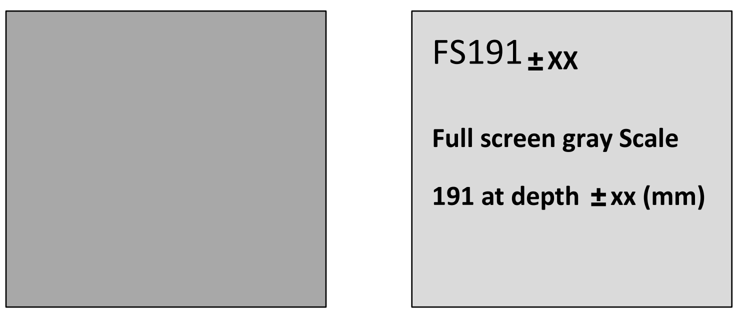

Figure 13. Full Screen Gray Scale Patterns (a) FS127, (b) FS191

For simplicity, we will use the full screen gray scale patterns. In some cases the IDMS1 is requesting to use a Harmonized Gray-Scale pattern. In Figure 14 we show one of these patterns as an example. In the IDMS1 it appears in Appendix §A12 (page 449).

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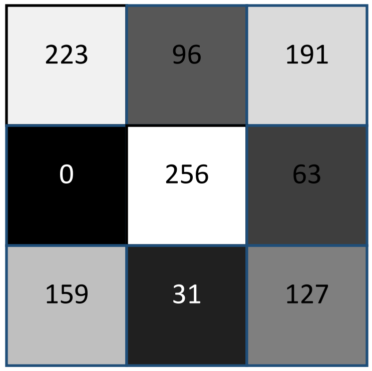

Figure 14. Harmonized Gray Scale Example (SCPL1)

6.6.5 Resolution Patterns (Grill). In Sections 2.5 and 4.3 we mentioned that for testing the depth, we will need to have either bit-mapped sequential white black lines, or sinusoidal lines. Figure 15 shows the bi-mapped alternating white black lines. The spacing in this case is one pixel.

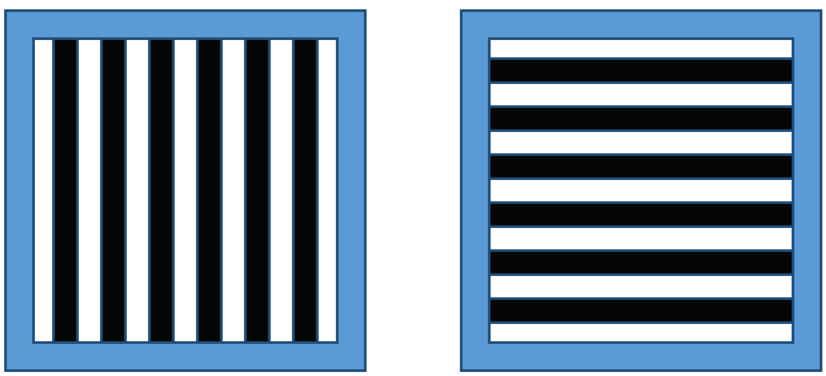

Figure 15. Resolution Lines Test Patterns (1 Pixel Wide): (a) Vertical and (b) Horizontal

The spacing of each line can be alternating grille of 1 pixel white / 1 pixel black lines, and is denoted at the IDMS1 [1] as *PGV1X1* for vertical and *PGH1X1* for horizontal (see Appendix §A12, page 451). The same patterns with 2 pixels width are labeled at the IDMS1 as *PGV2X2* and *PGH2X2* respectively (for Patterned Grille) and similarly for wider spacing.

We will keep the same notation, with the addition of the depth suffix (±xx (mm)) as in previous patterns above.

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With this notation we will have ***PGV2X2*** $_{\pm xx}$ for Grille of steps of 2 pixels white / 2 pixels black, in the vertical at a depth of xx (mm).

6.6.6 Resolution Patterns (Sinusoidal). Some of the resolution and depth tests are requiring sinusoidal grille pattern. This can be applied only for alternating lines (vertical or horizontal) that are several pixels wide. They will look similarly to Figure 3, but will have gradual slopes in luminance, similar to sinus curves.

Examples of sinusoidal patterns are in the IDMS1 [1] document in Section §17.5 (page 379) Fig. 1. They are copied here for reference in Figure 16.

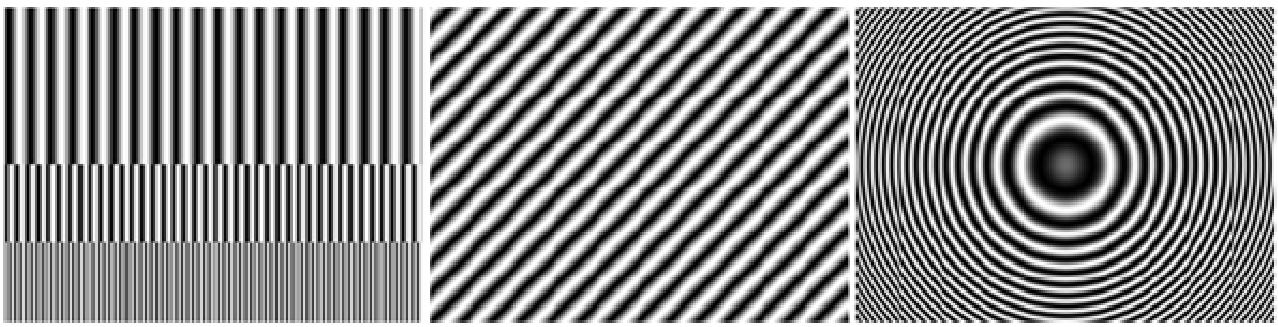

Figure 16. Examples of Sinusoidal Patterns (From the ICDM1 Section 17.5, Page 379)

As noted in the previous Sections 2.5 and 4.3, we will use these patterns for measurements of depth, by way of testing the resolution in several depths.

6.6.7 Checkerboard patterns. The checkerboard patterns are shown as an example in Figure 17. In this case we have 6 by 6 squares, half of which are black and the others are white. The IDMS1 notation calls this CB-6x6W which is Checker-Board with 6x6 squares with the upper left corner white.
We will use the same notation with the addition of the depth indication, for example $CB6X6W_{\pm XX}$ for the 6x6 checkerboard at depth XX (mm).

It is very desirable to have the checkerboard pattern with the white squares at one depth and the black at another. In this case we will denote this pattern:

$CB6X6W_{\pm XX}K_{\pm yy}$

- For checkerboard with 6x6 squares, where the white squares are at depth xx, and the black squares are at depth yy.

Although the IDMS1 is calling for several checkerboard patterns as shown in Appendix A12 on page 447, we will limit the patterns to one example (6X6), unless the display is very big.

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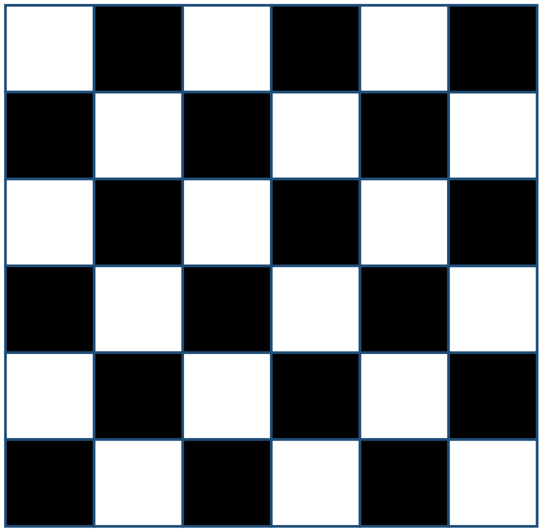

Figure 17. Checkerboard Pattern with 6X6 Squares

6.6.8 Alignment Tools. Most systems, like light-field displays, are coming with specific alignment tools and patterns unique to the structure of the display. Sometimes these patterns are not available to the customer. However, if they do, it is recommended to use them at least for visual inspection. Since these are individual to each display, they will not be detailed here.

6.6.9 Summary Table of Patterns. The following Table 3 is a summary of the patterns that will be used in these procedures. The table includes reference to the paragraphs above, as well as to the IDMS1 [1] page number. In some cases we have example, like FS127, which is full screen at gray scale 127. Patterns for visual inspections are discussed below.

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Table 3. Summary of Patterns

Pattern Type	Notation	Description	Figure # and comments	Reference
Full screen	**$FZ_{\pm XX}$ (Z=R,G,B,W,K)**	**Full screen at color Z (primary colors, white, black) at depth ±XX (mm)**	**Figure 11**	§6.6.2 (above) IDMS1 (pg. 446)
Grid	**$GRID_{\pm XX}$ (K/W, W/K)**	**Grid pattern (6x6 squares) with black lines on white background (K/W) or white on black (W/K)**	**Figure 12**	§6.6.3 (above) IDMS1 (pg. 449)
Gray Scale	**$FS127_{\pm XX}$**	**Full screen gray Scale 127 (for example) at depth ±XX (mm)**	**Figure 13**	§6.6.4 (above) IDMS1 (pg. 446)
Harmonized Gray Scale	**SCPL1**	**Follow the IDMS1 notation**	**Figure 14**	§6.6.4 (above) IDMS1 (pg. 449)
Grille (Resolution)	**$PGV2X2_{\pm xx}$ (for example)**	**Vertical alternating white / black lines with 2 pixels width, at depth ±XX (mm)**	**Figure 15 (**showing 1 pixel width, Vertical and Horizontal**)**	§6.6.5 (above) IDMS1 (pg. 451)
Sinusoidal Resolution	**See IDMS1**	**Follow the IDMS1 notation in section §17.5**	**Figure 16**	§6.6.6 (above) IDMS1 (pg. 379)
Checkerboard	**$CB6X6W_{\pm xx}$ (for example)**	**Checkerboard with 6x6 squares, white in upper left, at depth ±XX (mm)**	**Figure 17**	§6.6.7 (above) IDMS1 (pg. 447)
Checkerboard with 2 depths	**$CB6X6W_{\pm XX}K_{\pm yy}$ (for example)**	**Checkerboard (6x6) with white squares at depth ±XX and black squares at depth ±YY**	No figure	§6.6.7 (above) IDMS1 (pg. 447)
Alignment tools	**-**	**Individual patterns of each display (advice with the vendor)**	No figure	No Ref.

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6.7 Visual Inspection

It is recommended to do visual inspection of the display functionality and integrity before starting the display full evaluation. The patterns cited below and their notations were defined above (Section 6.6). Note that the procedure starts in sub-subsection 6.7.1 and completes in 6.7.2.

<u>Procedure</u>

6.7.1 Visual Inspection Procedures.

(1) Turn the **display ON**
   a. According to the vendor instructions
   b. Let it warm up as needed
   c. Once ready, position your head in the designed viewing location

(2) **Alignment tools** pattern
   a. Put the alignment tools on the screen
   b. Look for any irregularities
   c. If all is looking normal proceed to step (3)
   d. If there are problems, fix the problem, or advice with the vendor.

(3) Present **full screens,** each at a time, with the following patterns
   a. **White** at depth zero (FW_{00})
   b. **Black** at depth zero (FK_{00})
   c. **Red** at depth zero (FR_{00})
   d. **Green** at depth zero (FG_{00})
   e. **Blue** at depth zero (FB_{00})
   f. **Mid-Gray** at depth zero ($FS127_{00}$)

Watch for any non-uniformity issues. If there is any problem, check connections or other trouble shoot guidelines and fix before continuing to next steps.

(4) Present the **gridlines** pattern at zero depth ($GRID_{00}$), both the black lines on white background (K/W) and the reverse (W/K). Watch for any irregularities. Proceed to next step only if all is OK. Otherwise, check and fix the display system.

(5) Present the **checkerboard** pattern CB-6X6W at depth zero ($CB\text{-}6X6W_{00}$) and watch for:
   a. Uniformity of the squares
   b. Integrity of the overall image.
   c. Any traces of the black image into the white area – indication of crosstalk.

If all is OK, proceed to the next steps. Otherwise, trouble shoot the system.

(6) **If dual depth checkerboard** is supported:
   a. Select depth zero for the white squares, and depth -25 mm for the black squares ($\mathbf{CB6X6W_{00}K_{-25}}$)
   b. Inspect the integrity of the image at few viewing angles
   c. Reverse the pattern to have white squares at -25 mm, and black squares at zero depth ($\mathbf{CB6X6W_{-25}K_{00}}$)
   d. Inspect the integrity of the image at few viewing angles
   e. Pay attention to the border line between white and black squares

   If all is OK, proceed to the next step of visual inspection (images and movies).

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6.7.2 Typical 3D images for visual inspection.

(7) Use the **Hedgehog pattern** (proposed by Holografika):

a. The patterns are a special Appendix of IDMS1 on a separate folder, and will be supplied to this document later.
b. Figure 9 is showing one position of the 360 degrees rotation of the Hedgehog patterns.
c. This is a short movie that will present the rotating Hedgehogs, by switching from images Hedgehog000.png to Hedghog359.png in steps of 1 degree.
d. Please check if all is behaving normal and the Hedgehogs are rotating continuously, and showing all the colored pins properly.

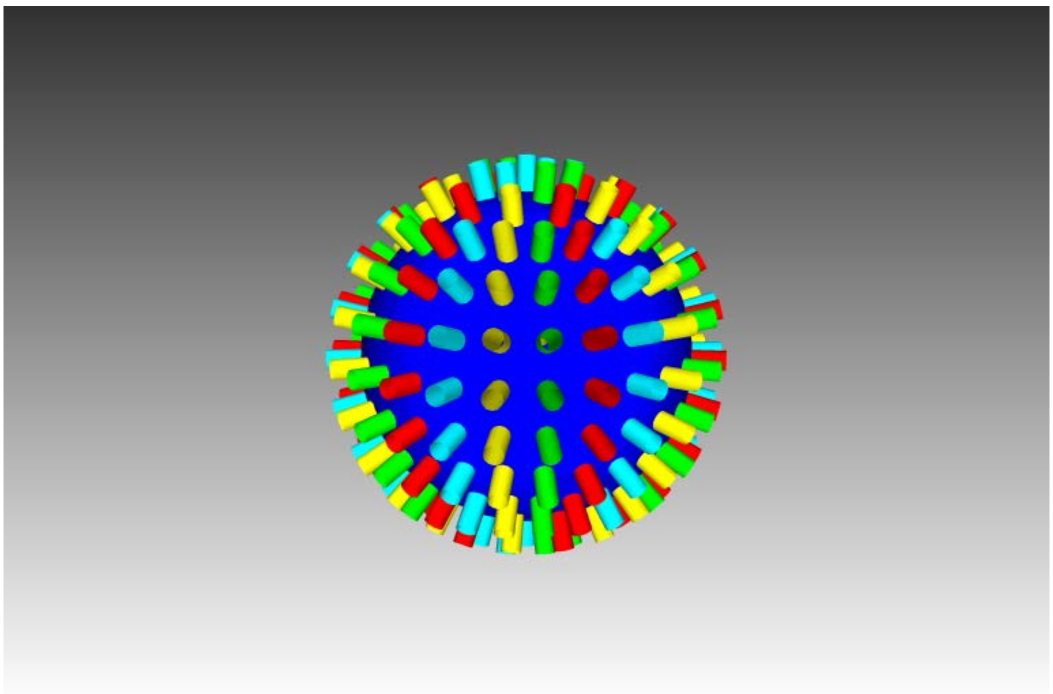

Figure 18. Hedgehog Pattern (1 out of 360) Rotating at 1° Steps

(8) **Vendors supplied image(s)**

a. Many display systems will have a typical demonstration image
b. Present these image(s) and look for any irregularities
c. If there is a problem, check the system. Otherwise, proceed to next steps

(9) **Demo Movie**

a. Some display system will have demonstration movie
b. Show the movie and watch for any problem

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6.8 Basic Measurements Procedures

In Section 4 above we analyzed the different basic modes of tests that are recommended in the IDMS1 [1] document. For instance, for Luminance Uniformity we can use either a spot-photometer taking 9-points measurement (sampled uniformity), or a photo-metric camera taking one shot (area uniformity). For this project we would like to have the set of photometers that were defined in Section 2.4 – Photometers Selection. Therefore we will use a camera for the uniformity tests, and so on. We are still in the process of checking the different photometers and cameras in the market to make decision which ones to use for the automated system.

Based on this we will define the following procedures, which several of them refer to the IDMS1 procedures.

6.8.1 Luminance Uniformity. As mentioned, we will use a photometric camera for these measurements. The specific type of camera that will be used is still being investigated.

<u>Procedure</u>
This method is using a photometric camera.

(1) Make sure that the camera has resolution of at last 50% of the display resolution
(2) Position the camera on the stand at a distance of 2570 times the pixels pitch (explanation are in the procedures at IDMS1 – Section §8.2, page 142)
   a. In some displays it will not be practical to move the camera this far away (2570 x pixels pitch) and we will have to put the camera at the best view location and distance.
   b. For lightfield displays the Hogels are the spacing or “pixels”
   c. For holographic displays the “pixels” are the lines separation of the information.
(3) Present a GRID pattern (or checkerboard) on the display at depth zero
(4) Focus the camera to get sharp image
(5) Follow the instructions of the IDMS1 Section §8.2 (page 142) to capture images of Full Screens at:
   a. Full White (FSW_{00})
   b. 20% Luminance
   c. 5% Luminance
   d. Full Dark (FSK_{00})

Comment: You first have to find which Gray Scale level matches the 20% and 5% luminance (see IDMS1 section §6.1 page 87).

(6) Once the images are captured by the camera and interface –
   a. Rotate the image to match the orientation of the camera versus the display
   b. Crop the image to eliminate edge effects, and match to the edge of the active area
   c. If you see Moiré effect in the captured images, repeat the measurement by taking these steps:
      i. Defocus the optics
      ii. Apply low pass filter in the Fourier domain
      iii. Tilt the camera slightly

Comment: These steps are compatible with the IDMS1 procedure

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(7) Analysis – should follow the instructions at IDMS1 - §8.2.2 (page 145).
   a. The maximum deviation is defined as:
      i. $\Delta L_{max} = 100\% * (1 - L_{max} / L_{min})$
   b. The RMS-Luminance – see the IDMS1 equation (1) PAGE 145
   c. Target number: $\Delta L_{max} < 40\%$, assuming that this is edge to center variation.

(8) Additional analysis (optional):
   a. 3D graphic presentation of the data (see IDMS1 §8.2 page 143)
   b. Cross section of the data along defined axis (horizontal, vertical, diagonal) – see top of the figure on page 143.
   c. Histogram of the luminance data (not shown in page 143)

Comment: These are common presentation of general images, and can point to a trend or a problem if viewed. These are optional.

6.8.2 Small Area Uniformity. Using the same captured camera images of the luminance, the data analysis can detect the small area uniformity. It can find any blotches or other local artifacts (Mura) that are visible. Checking for Mura will prevent having a bad looking display.

<u>Procedure</u>

(1) Use the images captured for the Luminance Uniformity (above Section 3.4.1)

(2) Follow the Mura analysis - IDMS1 Section §8.2.3. (Page 146 ~ 149).
   a. The image is first going a smoothing algorithm (down-sampling) to reduce noise and small variations.
   b. Then the image is processed with a filter, which is effectively making first derivative.
   c. Then the local variations are recorded, and explained (IDMS1 Section §8.2.3., Pages 146 ~ 149)
   d. The reporting is of number of MURA points and the luminance just noticeable difference (L-JND) value for each blob.
   e. Passing criteria: L-JND = 1 is the limit. Points with L-JND < 1 are OK. Points with L-JND > 1 will be noticed by the human eye.
   f. This is equivalent to measuring the luminance difference within a small distance on the screen. In most cases 3% ~ 5% luminance difference is noticed.

6.8.3 Color Uniformity. Color uniformity can also be measured with either a spot-photometer (Sampled uniformity at 5 or 9 points), or with the color photometric camera (area measurement). In this project we intend to use the camera. We will skip the sampled uniformity (see IDMS1 section §8.1.2, page 140) which already discussed in Section 3.6. However, there are no specific instructions in the IDMS1 for area color uniformity.

As mentioned, we will use a photometric camera for these measurements. The specific type of camera that will be used is still being investigated.

<u>Procedure</u>

(1) Make sure that the camera has resolution of at last 10% of the display resolution. The reason for this low resolution is that we are sampling down anyhow, as for the MURA test.

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(2) Position the camera on the stand at a distance of 2570 times the pixels pitch (explanation are in the procedures at IDMS1 – Section §8.2, page 142)

a. In some displays it will not be practical to move the camera this far away (2570 x pixels pitch) and we will have to put the camera at the best view location and distance.
b. For lightfield displays the Hogels are the spacing or "pixels"
c. For holographic displays the "pixels" are the lines separation of the information.

(3) Present a GRID pattern (or checkerboard) on the display at depth zero

(4) Focus the camera to get sharp image

(5) Capture images of Full Screens for the primary colors at depth zero:

a. Full Red (FSR_{00})
b. Full Green (FSG_{00})
c. Full Blue (FSB_{00})
d. Full White (FSW_{00})
e. Full Black (FSK_{00})

(6) Once the images are captured by the camera and interface –

a. Rotate the image to match the orientation of the camera versus the display
b. Crop the image to eliminate edge effects, and match to the edge of the active area
c. If you see Moiré effect in the captured images, repeat the measurement by taking these steps:
   i. Defocus the optics
   ii. Apply low pass filter in the Fourier domain
   iii. Tilt the camera slightly

(7) Analysis –

a. Down-sample (smoothing algorithm) the image to about 300 pixels width.
   i. Depending on the resolution of the camera the factor will be defined.
   ii. The procedure is similar to the MURA test, described on the IDMS1 - §8.2.3 page 146, step 4. of the Analysis.
b. Calculate the mean (u', v') color coordinates of each down-sized pixel (i, j)
c. Calculate the vector difference between all combination of pixels using the formula:

Equation 5 - $\Delta u'v' = sqrt\ (\ (u'_1 - u'_2)\text{^}2 + (v'_1 - v'_2)\text{^}2\ )$

Sqrt = square root
^2 = to the power of 2
(u'_1, v'_1) and (u'_2, v'_2) – are two points of color on the map for each of the down-sized pixels.

(8) Report the maximum $\Delta u'v'$ as the color tolerance per each of the primary colors

(9) Additional analysis (optional):

a. Plot the colors of all the pixels in a CIE-u'-v' (1976) color map (for each primary color)

(10) A typical tolerance of $\Delta u'v'$ = 0.015 will be acceptable across the display panel for the primary colors.

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Alternative procedure
In case that the camera is non-color, but there is a spot-photometer, we recommend to follow the procedures of sampled uniformity at 9 points, described on the IDMS1 – Section §8.1 – page 138.

6.8.4 Color Differences in Small Area. The color uniformity map, measured with a color photometric camera, allows us to make further analysis. We would like to make sure that there are not significant color shift between Hogels or any high gradient of color changes across small area. Similarly to the color uniformity, this measurement is done at normal view.

Procedure
(1) Use the down-sampled images of the previous section §7.8.3 step-(7).
(2) Compare each pixel of these images (for each of the primary colors) with its neighbors for difference in color (*Δu'v'*) as defined in the previous section.
(3) Report any location when the difference exceeds the limit of *Δu'v'* = 0.005.

6.8.5 Contrast Ratio / Uniformity. The contrast ratio (CR) is the ratio of white field over black field. The higher the CR, the image quality will improve. A minimum of 100:1 ratio will be considered OK in most cases. The higher, the better.
In stereoscopic displays, the CR can be measured in each channel (each eye). Most stereo and autostereoscopic displays will have similar CR in both channels.
In FoLD it is also very important to have high CR in order to improve the 3D effect and depth perception.

Procedure (sampled method)
This method is using a spot-photometer.

(1) Turn the display ON and let it warm up (as recommended by the vendor)
(2) Present GRID pattern or checkerboard and focus the spot-photometer on the patterns
(3) Present a Full Screen White pattern (FSW_{00}) at depth zero.
(4) Measure the 9 points luminance as described in IDMS1 – section §8.1 page 138. The 9 points are described in Figure 19
(5) Present a Full Screen Black pattern (FSK_{00}) at depth zero.
(6) Measure the 9 points luminance
(7) Calculate the Contrast Ratio (C_i) for each of the 9 points:
    a. $C_i = L_{wi} / L_{ki}$
    b. Where: C_i- is the contrast ratio of point (i), and L_{wi}, L_{ki} – are the white and black luminance of this point (i).
(8) The procedure is detailed in IDMS1 section §8.1.1 page 139.
(9) Report
    a. The Contrast Ratio at center
    b. The non-uniformity of the contrast ratio

$$N = 100\% * (1 - C_{min} / C_{max})$$

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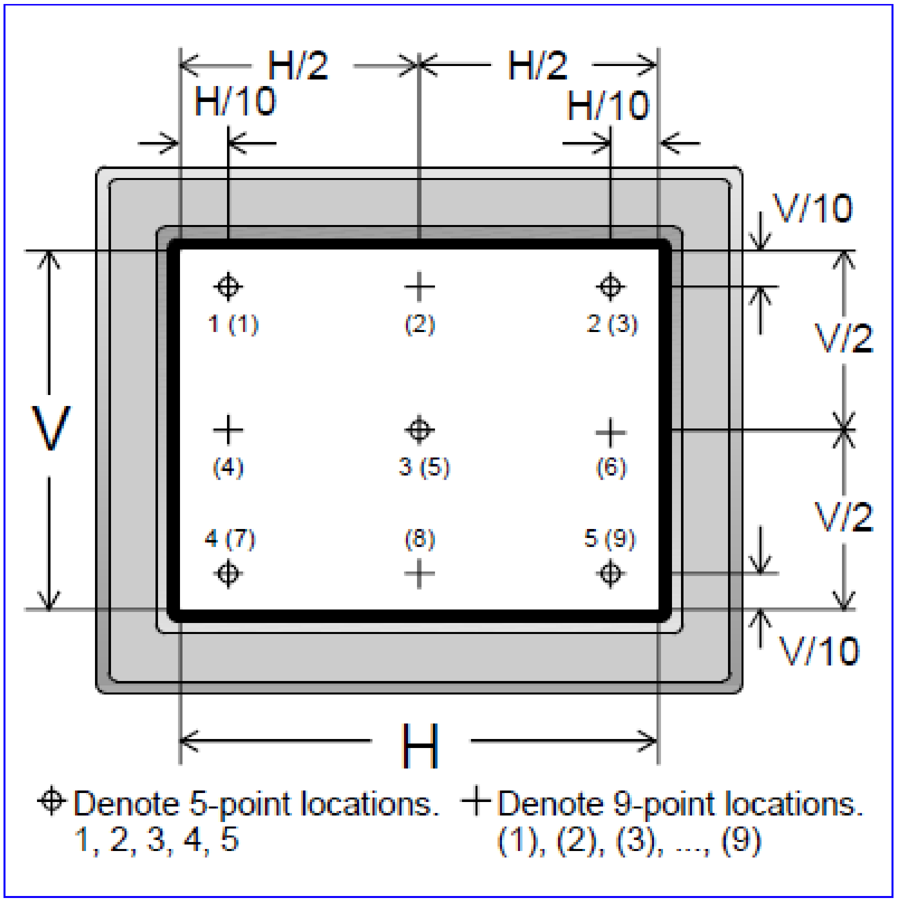

Figure 19. Sampled Uniformity Measurement Points (5 or 9 Points)

Procedure (area method)

This method is using a photometric camera (monochrome or color). The procedure is similar to luminance uniformity.

(1) Make sure that the camera has resolution of at last 10% of the display resolution. The reason for this low resolution is that we are sampling down anyhow, as for the MURA test.

(2) Position the camera on the stand at a distance of 2570 times the pixels pitch (explanation are in the procedures at IDMS1 – section §8.2, page 142)
   a. In some displays it will not be practical to move the camera thus far away (2570 x pixels pitch) and we will have to put the camera at the best view location and distance.
   b. For lightfield displays the Hogels are the spacing or "pixels"
   c. For holographic displays the "pixels" are the lines separation of the information.

(3) Present a GRID pattern (or checkerboard) on the display at depth zero

(4) Focus the camera to get sharp image

(5) Capture images of Full Screens for the white and black at depth zero:
   a. Full White (FSW_{00})

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b. Full Black (FSK_{00})

(6) Once the images are captured by the camera and interface –
   a. Rotate the image to match the orientation of the camera versus the display
   b. Crop the image to eliminate edge effects, and match to the edge of the active area
   c. If you see Moiré effect in the captured images, repeat the measurement by taking these steps:
      i. Defocus the optics
      ii. Apply low pass filter in the Fourier domain
      iii. Tilt the camera slightly

(7) Analysis –
   a. Down-sample (smoothing algorithm) the image to about 300 pixels width.
      i. Depending on the resolution of the camera the factor will be defined.
      ii. The procedure is similar to the MURA test, described on the IDMS1 - §8.2.3 page 146, step 4, of the Analysis.
   b. Calculate the contrast ratio for each of the down-sampled pixels as white / black:
      i. Contrast Ratio $C_u = L_W / L_K$
      ii. Dividing each matching white pixels by the same pixel in black.
   c. More details are in IDMS1 Section §8.2.1 page 144.
   d. Once you have the Contrast Ratio Cu map, proceed to IDMS1 Section §8.2.2 page 145 for the analysis and reporting of the non-uniformity in contrast ratio.
   e. Plot the Cu map. It can show: the Contrast Ratio at the center, the minimum point, and also local variations.

6.8.6 Recommended sequence of measurements. So far we covered several measurements, some of which can be done together, like luminance, colors and contrast ratio uniformity. In this section we would like to recommend of optimal sequence of measurements. Table 4 lists the measurements that can be combined, and then do calculations and reporting in a raw. It uses short notations as used in previous sections.

Conditions:

(1) Available: Spot-photometer + Mono Camera
   a. Do all listed measurements (for both)

(2) Available: Spot-photometer + Color Camera
   a. Do only center point with spot-photometer, and all other listed measurements with the camera

6.8.7 Angular Luminance Drop. Displays should have enough brightness. A minimum of 150 cd/m^2 is required in relatively dark room (~ 10 Lux). Much higher (e.g. 300 cd/m^2) is desirable in well lit room.

Some display systems reduce the normal view brightness over angles. We would like to measure this. This drop in luminance has two problems: (a) overall luminance is low, and (b) when viewing a large display it will have significant luminance variation between the center and a corner.

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Table 4. Optimal Sequence of Measurements

Available equipment	Measure	Calculate	Report
Spectra-spot-photometer	9 points: Lum, U'V' – Full screen - W,K,R,G,B	Lum, *Δu'v'*, Cu(W/K) – Non-uniformity	Center: Lum(W); CR Non-Unif: Lum, *Δu'v'*, Cu
High Resolution mono-camera	Full screen (Lum.): W,K, S127, G20%,G05% (gray)	Contrast (Cu=Lw/Lk); Non-unif. W, Cu, Gray	Non-unif. W, Cu, Gray Maps: W, Cu MURA
Color camera	Full screen (Lum, U'V'): W,K,R,G,B, S127, G20%, G05% (Gray)	Contrast (Cu=Lw/Lk); Non-unif. W, Cu, Gray *Δu'v'*-for R,G,B	Non-unif. W, Cu, Gray Maps: W, Cu MURA Differ.- *Δu'v'* for RGB Color maps

There are three options to make the angular measurements:
(a) Spot photometer on a rotating goniometric stage
(b) Conoscopic camera
(c) A camera on a goniometric stage
Spot photometer on the goniometer will be adequate for sampled viewing angles. This is a slow measurement and therefore will be enough to take few measurements over the angles. This method is flexible to be used with most of the 3D displays, including stereo and FoLD.

The conoscopic camera is very effective and gives the complete set of measurements in fast and accurate measurement. However, it will not work with displays that don't have access to their surface. In this category will be most of the FoLDs.

A camera mounted on a goniometer will give much information. However, we have to be very careful with extreme tilted angles. In each angle, the camera has to be corrected for the oblique view. Techniques used in automated inspection of tilting the lens with the rotation, are fairly complex, and will be considered during the final construction of the automated system, but as second option.

We will use the spot-photometer mounted on a goniometer, and focused at the center of the display. This will fit most of the FoLD displays.

This topic is well covered in the IDMS1, Section 9, pages: 150-167. The Luminance Drop measurement we adopted appears in Section §9.1 - Four Point Viewing Angle (page 152). For reference, Figure 20 below is a copied image of the set-up used at this section for the testing (Fig. 1. page 152).

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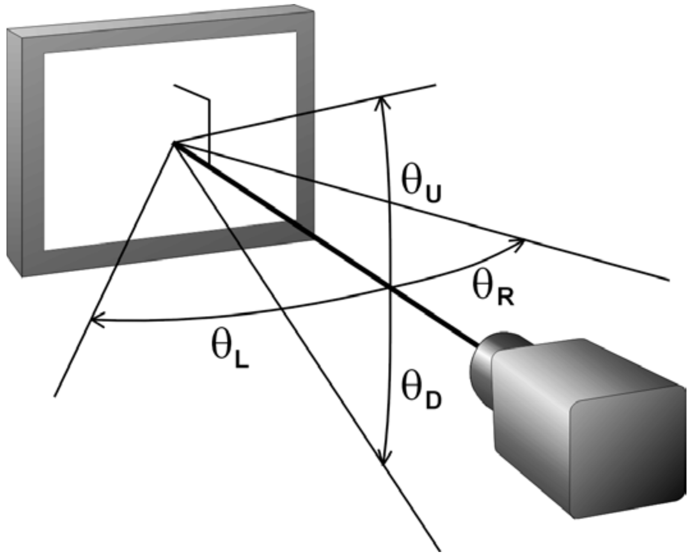

Figure 20. Four Point Viewing-Angles

Procedure
(1) Turn the display ON and let it warm (as recommended by the vendor)
(2) Present a GRID of Checkerboard pattern
(3) Using a spot photometer mounted on a goniometer
(4) Position the photometer at normal view
(5) Focus the photometer optics on the display image
(6) Present on the display:
   a. Full Screen white (FSW_{00}) at depth zero
(7) Take a luminance (and color) measurement
(8) Move the goniometer to angles:
   a. θ_R = +30° H – horizontal 30 degrees to the right
   b. θ_L = -30° H – horizontal 30 degrees to the left
   c. θ_U = +30° V – Vertical 30 degrees up
   d. θ_D = -30° V – Vertical 30 degrees down

For each angle make sure that the photometer is still focused at the center, and take Luminance (and color) measurement.
(9) Record the luminance and color information for each angle
(10) Report: Report the luminance for each angle

6.8.8 Angular Color Shift. It is important to have displays that show minimal variation of color shift over angles. There are few reasons:
(a) We don’t want to lose color saturation over angles, which is mostly the case
(b) While viewing a 3D display from a designed eye position, we sometimes see sections of the display at oblique angle, and some other at close to normal. If there is a significant change in color, it will show badly on a uniform color area.
(c) Color mixing will be a problem over angles, since many times the change in the three primary colors is not the same for each color.

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Color change over angles will be measured in the same way as luminance over angles. We will use the same IDMS1 Section §9.1 - Four Point Viewing Angle (page 152).

<u>Procedure</u>

(1) Repeat the procedures steps of the luminance over angles (§7.8.7 above), except:

(2) On step (6) above have several screens:
   a. Full Screen white (FSW_{00}) at depth zero
   b. Full Screen Black (FSK_{00}) at depth zero
   c. Full Screen Red (FSR_{00}) at depth zero
   d. Full Screen Green (FSG_{00}) at depth zero
   e. Full Screen Blue (FSB_{00}) at depth zero

(3) Record the data for all screens and for all 5 viewing angles.

(4) <u>Report</u>:
   a. Use the table at IDMS1 section §9.1 on page 152 to report. Here is a copy of the table for reference (see Table 5).

Table 5. Copy of IDMS1 Reporting Table for Luminance and Colors over Four Viewing Angles (Plus Normal)

—SAMPLE DATA ONLY— Do not use any values shown to represent expected results of your measurements.										
Analysis and Reporting — Viewing Angle Sample Data										
Direction	Angle	White				Black				
		L_W	x_W	y_W	CCT	L_b	x_b	y_b	C	
Up: θ_U	15°	85.6	0.298	0.322	7478	1.59	0.271	0.292	52.9	
Down: θ_D	10°	111	0.322	0.348	5967	3.79	0.269	0.285	29.2	
Right: θ_R	30°	39.4	0.323	0.346	5903	0.553	0.268	0.290	71.2	
Left: θ_L	30°	39.9	0.323	0.345	5920	0.609	0.270	0.297	65.4	
Direction	Angle	Red			Green			Blue		
		L_{red}	x_{red}	y_{red}	L_{grn}	x_{grn}	y_{grn}	L_{blu}	x_{blu}	y_{blu}
Up: θ_U	15°	25.9	0.521	0.350	50.2	0.296	0.521	16.1	0.157	0.140
Down: θ_D	10°	35.4	0.520	0.349	63.5	0.305	0.518	20.3	0.166	0.165
Right: θ_R	30°	12.1	0.550	0.354	22.5	0.307	0.541	6.23	0.158	0.150
Left: θ_L	30°	12.3	0.548	0.353	22.7	0.306	0.540	6.34	0.158	0.150

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6.8.9 Temporal Variations, Visible Flicker. Temporal measurements are important and include several aspects. We would like to focus on two major ones: (a) flicker, and (b) effects that reduce video quality.

Since this is a big topic and is covered well in the IDMS1 procedures, we will rely on this document and will not detail much here, except for some comments.
See: IDMS1 Section §10. Temporal Measurements, page 168 and on.

6.8.9.1 Flicker. The flicker is a phenomena that might cause nausea if severe, therefore it is important to reduce it below the threshold frequency that the eye can distinguish and with minimal changes in luminance levels between image frames. It should be measured with a fast responding photometer or optical sensor, and analyzed in a signal storage device.

<u>Procedure</u>
The procedures are defined in IDMS1 section §10.5 Flicker (pages 180-181).

<u>Comments</u>
The method is to record the signals and analyze them in the Fourier domain where amplitudes (or flicker level) are plotted as a function of frequency. The highest level is reported. For typical light illumination, and frequencies that are above 24 frames per second, we would like the flicker to be below 5%.

These methods are general and should be applicable to any of the FoLD displays. It is most important to include them in the set of tests for displays that have scanning, for example, the Acuity 3D display.

6.8.10 Video Smearing. In 3D displays that are showing video images, it is important that there will be minimal smear of the images. This topic is also covered in the IDMS1 Section 10. Temporal Measurements, page 168 and on.

<u>Response time</u>
There are several phenomena affecting the smear. The most important one is the response time of the system, explained in Section 10.2 (page 169). For example, a slow responding liquid crystal (LC) material will change the optical effects slowly between the frames. This will cause for a moving ball across the screen to have an unwanted trail, like a comet in the sky. We would like the response time as defined in that IDMS1 section to be below the frame time (<16.7 msec).

Other phenomena that can affect the smear is latency of the display. We would like that after the frame the image will disappear fast, before writing new information.

As mentioned, this topic is covered well in the IDMS1 and we would like to follow the procedures that are there. They will be applicable to FoLDs.

6.8.11 Artifacts–Visible. This is a visual test, and should be done with a uniform luminance field, like full white.
<u>Procedure</u>

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The viewer should position himself in a typical view location and record whether there are visible artifacts. Such are including the structure of the pixels, patterns (e.g. film-patterned-retarders), parallax barrier strips, lenticular lenses, lens array (as in Light-Field), or any other structural effects.

The eye is very sensitive to dominant frequencies, and therefore can identify the structure as long as it is within the limit of the sensitivity curve for the specific lighting conditions. In most cases the frequency limit is about 50 line pairs for degree as shown in few curves in Peter Barten's book about the sensitivity of the eye and the papers [25, 26, 27].

Since the sensitivity is a function of the luminance levels, and angular resolution, it should be done at the targeted view location(s), including view distance as short as the display was meant to be used.

More specific, for the Light-field displays, we would like that the size of the micro-lenses will be small enough that the eye will not distinguish it. This means that it will be around 0.3 mRad (1 arc-min). This is about 0.1 mm from 330 mm view distance. For other FoLDs this means that any structure on the display should be smaller than the eye ability to notice it.

6.8.12 Basic Measurements–Summary Table.

Let's summarize the basic measurements of the displays and the reference location in the IDMS1 document. Below is a summary Table 6.

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Table 6. Basic Measurements and the IDMS1 Reference

Test	Method	Recommended equipment	comment
Luminance (Lum)	Spot measurement (center sample; optional 9 points)	Spot-photometer	§7.8.3 ; IDMS1-Section 8.1 (page 138)
Luminance uniformity	Area measurement	Camera (correction needed)	§7.8.1; IDMS1-Section 8.2 (page 142)
Small area Lum uniformity	Area meas.	Camera (Mura analysis)	§7.8.2; IDMS1-Section 8.2.3 (page 146~149)
Color uniformity	Area meas.	Color camera	§7.8.3; IDMS1-Section 8.2.3 (page 146)
Small area color variations	Area meas.	Color camera (Δu'v' calculations)	§7.8.4; IDMS1-Section 8.2.2 (page 145)
Contrast Ratio (C_u)	Area meas.	Camera (W /K fields)	§7.8.5; IDMS1-Section 8.2.1 (page 144)
Angular luminance drop	Spot measure at display center	Spot-photometer / goniometer	§7.8.7, at four angles; IDMS1-Section 9.1 (page 152)
Angular color shift	Spot measure at display center	Spot-photometer / goniometer	§7.8.8, at few angles; IDMS1-Section 9.1 (page 152)
Temporal variations, flicker	Fast sensor + signal capture	Fast spot-meter / signal processing	§7.8.9; IDMS1-Section 10.5 (page 180)
Video smearing	Fast sensor + signal capture	Fast spot-meter / signal processing	§7.8.10; IDMS1-Section 10.2 (page 145)
Artifacts - visible	Visual	Use test patterns	§7.8.11

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6.8.13 Target Numbers. The following Table 7 is a summary of target values for the measurements.

Table 7. Target Numbers for Measurements

Parameter	Condition	Min/Max value	Units	Measured procedure	Equipment	Comments
Luminance @Center	At normal view	200	Cd/m^2 (Min)	§6.8.3	Spot-Photometer	
Luminance Uniformity	9 points sampled	30	% (Max)	§6.8.3	Spot-Photometer	
Luminance Uniformity	Area (@normal)	30	% (Max)	§6.8.1	Camera	
Small area Lum. Unif.	Area (@normal)	5	% (Max)	§6.8.2	Camera	
Color Uniformity	9 points sampled	0.015	$\Delta U'V'$ (Max)	§6.8.3	Spot-Photometer	
Color Uniformity	Area (@normal)	0.015	$\Delta U'V'$ (Max)	§6.8.3	Color camera	
Small area color variations	Area (@normal)	0.005	$\Delta U'V'$ (Max)	§6.8.4	Color camera	
Contrast Ratio (C_u)	Area (@normal)	100	ΔC_u (Max)	§6.8.5	Camera	
Angular luminance drop	@center	50	% (Max)	§6.8.7	Spot-Photometer / Goniometer	
Angular color shift	@center	0.015	$\Delta U'V'$ (Max)	§6.8.8	Spot-Photometer / Goniometer	
Temporal variations, flicker	@normal	5	% (Max)	§6.8.9	Fast photometer or sensor	
Video smearing	@normal			§6.8.10		
Artifacts – visible	@normal			§6.8.11		

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7.0 3D DEPTH NEW METHODS

In section §3.4 above (3D depth perception and resolution) we discussed the fact that the depth of stereoscopic displays are mostly influenced by the crosstalk. For light-field and other Field of Light Displays (FoLD) there is no separation between left and right eye. The depth perception is coming from a separation to each eye by directional rays. Therefore this is mostly influenced by the resolution of the display, the ability to control the rays in space, and somewhat by the display contrast.

We would like to propose three steps of depth evaluation:
(a) Visual – using a typical image including depth (both behind and above the displays surface)
(b) Focus of computer generated images (Lee's method [24])
(c) Resolution tests at several depth

7.1 Visual Assessment

As in other tests, a visual inspection is best to proceed before elaborated test. Each display technology will have some limitations. However, we can use a typical image for this purpose.

<u>Image patterns</u>

Please refer to section §3.3 and more detailed instructions in §7.7 – Visual Inspection (above) proposing patterns for visual inspection.
The inspection is done in steps as described in the above sections. Please follow the patterns.

More specific, the IDMS1 is proposing to use the Hedgehog rotating balls with colored pins (Figure 18 above) as a moving patterns indicating 3D capability. Please refer to section §7.7.2 - Typical 3D images for visual inspection.

7.2 Computed Patterns (Lee's Method)

Lee et al [24] proposed to use a computer generated images (called Computational Integral Imaging reconstruction-CIIR) of a triangle and a circle shown side by side. They control the depth difference between the triangle and the circle. Then they change gradually the depth difference and position the images. The viewer has to specify which image is in focus, and which not. If there is big difference between focused and non-focus images it will indicate that there is good depth separation in the display. In the following image from Lee (Figure 12) we see that the triangle is blurry while the circle is mostly focused. In this case by computation, the difference between the patterns is 20 mm, and therefore this is resolvable in this system.

<u>Procedure</u>
(1) Using computational Integral Imaging Reconstruction (CIIR) – present the Lee's image (triangle, and circle with cross) side by side, at different depth (e.g. depth separation of 20 mm between the circle and the triangle, when the circle is at zero).
(2) Watch if one image is in focus, and the other not, or else.

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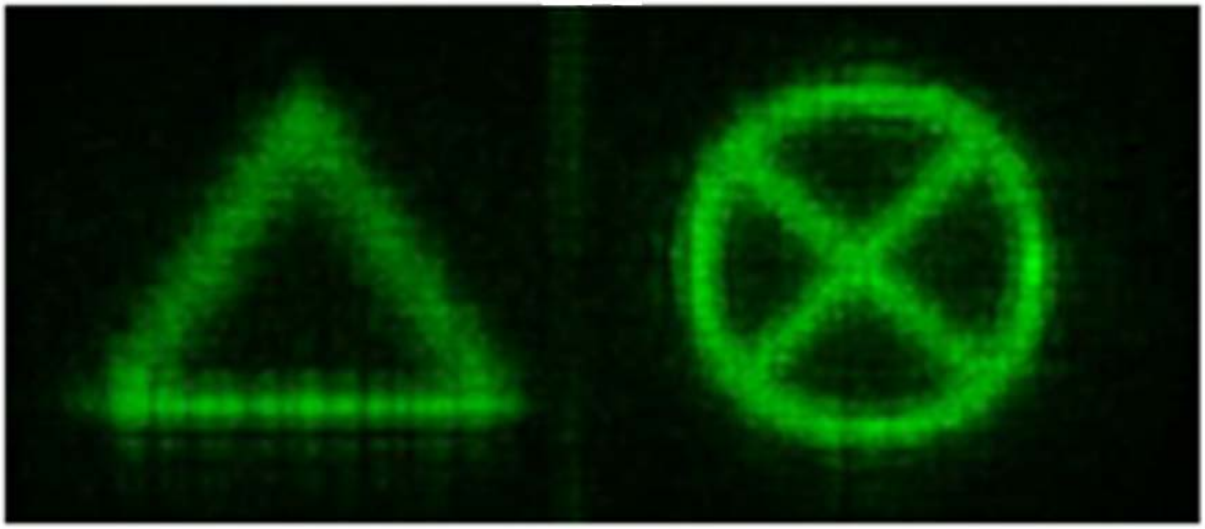

Figure 21. Triangle and Circle - From Lee's Paper

(3) Report your observation
(4) If one image is in focus and the other not, this indicates that there is a depth separation of at least the depth set in step (1) by the CIIR.
(5) Repeat with different depth separations and overall depth set-up
(6) Record and plot the results.

Comments: Although this method is partially visual, the set of depth by the CIIR is numeric and can give good numerical values for the display system.

7.3 Depth Resolution Measurement

The method proposed by Koike [6] is summarized in the IDMS1 [1] section §17.5.4, page 378. It refers to measurement of modulation transfer function (MTF) at a given depth.

The image presented on the display is a sinusoidal pattern with modulation in the horizontal direction, vertical, or diagonal. The image is designed at a specific depth, starting with zero depth (at the display surface, or in some cases in the air). The signal is viewed and measured by a high resolution camera, with pixels of at least x2 the number of pixels of the display. Preferably even x10 times as many pixels as in the display. Care should be taken to minimize Moiré effect, by either slightly defocus the lens, or small tilt of the camera (e.g. 5°).

Example of sinusoidal patterns are in Figure 22 taken from the IDMS1 [1] section §17.5.4, page 379, or as presented earlier in the patterns section (Figure 16).

Once the image is captured, a horizontal (or vertical) cross section will be derived to get a signal over location curve. This signal will be divided by the input signal to get the relative modulation signal. The MTF will be calculated by taking the peak signal and divide by the valley signal.

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This will be done for several peaks and valleys and then averaged. Example of captured normalized curves for several depths are shown in Figure 23.

Note that the plots are normalized to the sinusoidal pattern and the horizontal axis is the depth (z) divided by the display diagonal dimension (D). It should be divided by the view distance (L), but this metric is more systematic and give similar results.

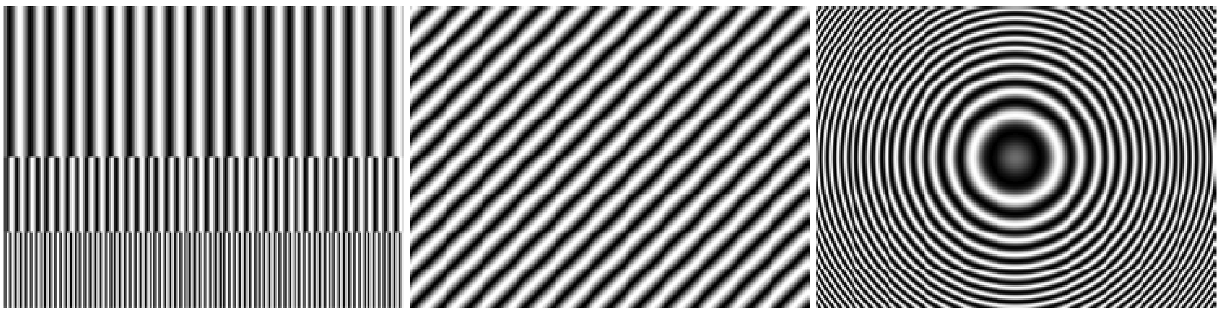

Figure 22. Example of Sinusoidal Patterns (Horizontal, Diagonal, Circular) From IDMS1 Section 17.5.4

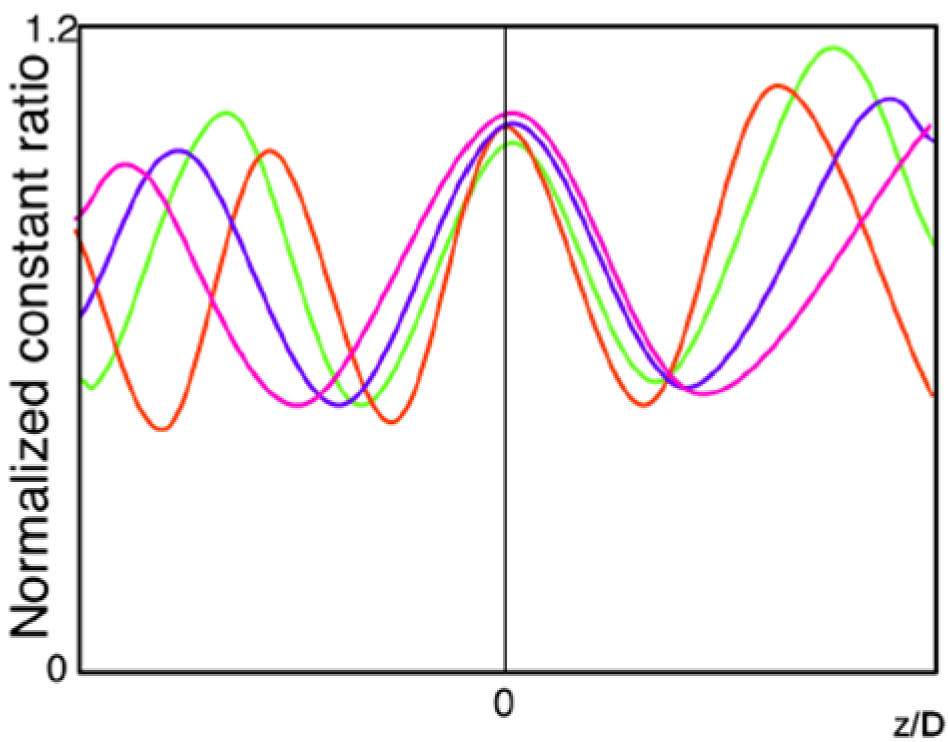

Figure 23. Normalized Sinusoidal Contrast Plots Captured in Few Depths From IDMS1 Section 17.5.4.

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Once we have the 2D resolution from this analysis, we can use the ratio:

Equation 6 - $$B_{2D} = B_{3D}*N = B_{3D}*(w / P_{ix})$$

Where:

B_{3D} – is the resolution measured at a given depth (therefore it is 3D)
N – is the number of pixel along horizontal (or vertical)
w – is the display width (horizontal); or in the vertical will be (h)
P_{ix} – is the number of pixels along horizontal (or vertical)

The meaning of equation 6 – is that we are calibrating the depth by using the horizontal (or vertical) display dimensions and number of pixels.

Recording this for a light-field display will give the depth resolution as shown in Figure 24, also taken from the IDMS1 [1] Section 17.5.4.

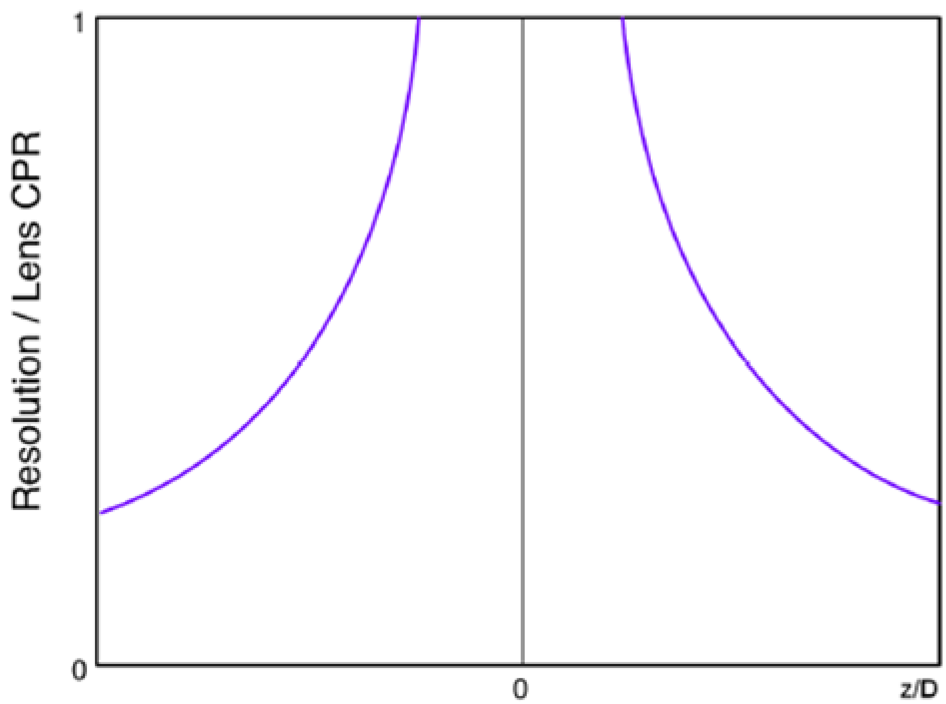

Figure 24. Example of the Resolution Limit versus Depth from IDMS1 Section 17.5.4

This plot is the normalized resolution by the lens steps in the vertical axis, and depth normalized by the display diagonal in the horizontal axis. As we see the resolution is best close to the display surface, where the depth z (or the ratio z/D) is close to zero.

This method is focused at the IDMS1 procedures for the Light-field displays, but is generic for any FoLD display. In other cases the MTF normalization will be the same. The depth (z) will be normalized by the view distance (L).

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8.0 TEST SYSTEM CONFIGURATION

In previous sections we defined the tests and procedures. In this section we will talk about the test system and its components, including the photometer on which we had some discussion before. The focus is on the hardware and software of the automated photometric test system. We investigated several potential photometers and their specifications to match the test procedures detailed in the previous section. We find that photometric cameras are more efficient. The camera is mounted on a scanning stage.

The test system includes scanning stage, spot-photometer and photometric-camera, support software and dedicated software that we will develop. The reporting will be in tables compatible with Excel. Additional procedures will be developed for depth measurements and are detailed.

A general flow chart for the tests is shown in Figure 25 (similar to Figure 10). We start with an alignment process, in which we adjust the test equipment position to the display center, and orthogonal to its surface. We will use cross hair pattern on the display for this process. The fine tuning of this process will include manual motion of the stages (x, y) and zero set in the software. Description of the coordinate system that we will use is detailed in Figure 26 below.

8.1 The Test System Will Include

(1) Mechanical stages with motors to control motion, and controls that are computer activated.
(2) Spot photometer (preferably spectra-spot-photometer)
(3) Photometric camera
(4) Temporal measurement device – sensor, preamplifier and interface to an oscilloscope or to the computer
(5) High resolution photometric camera – for resolution measurements
(6) Range-finder device, modified for our tests – for depth measurements
(7) Power supplies and controller boxes
(8) Computer for image presentation – can be part of the display system
(9) Computer for tests control and data accumulation – the test system computer

For this description, we would like to use the following coordinate system, described in Figure 26.

As mentioned, we will have a process to align the stage to the center of the display. Therefore X=0, Y=0 will be at the center of the display.

The value of Z =0 when the photometer, or camera are set at the proper distance for focusing. This will be discussed later.

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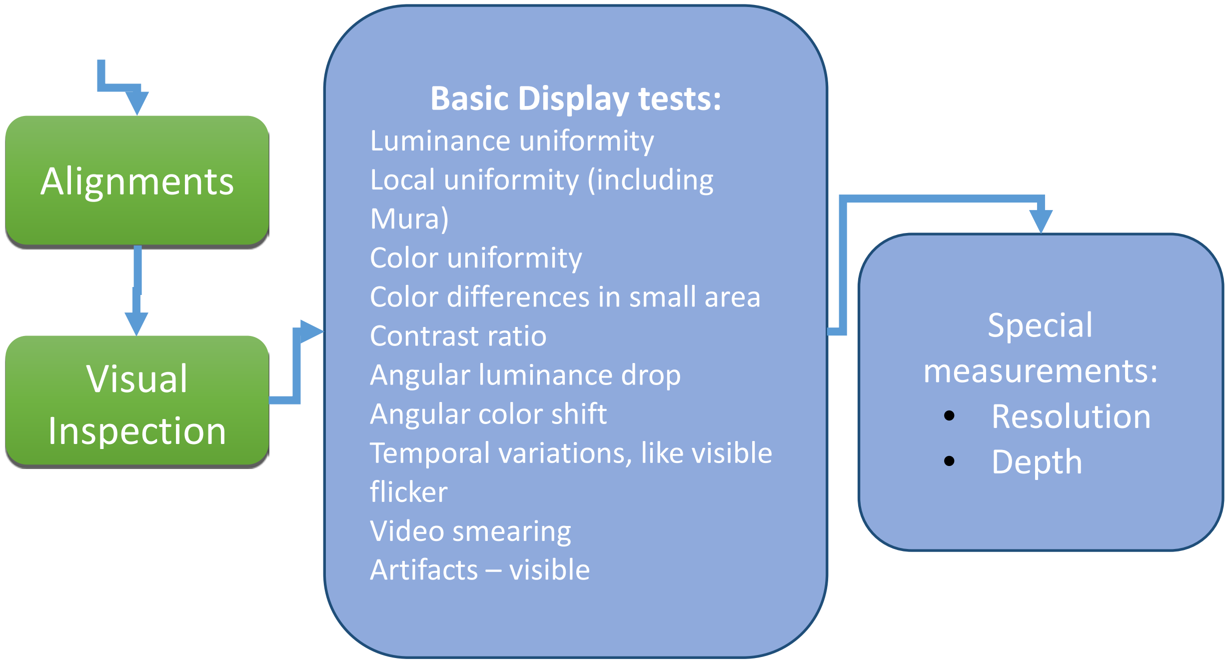

Figure 25. Flow Chart of Measurements

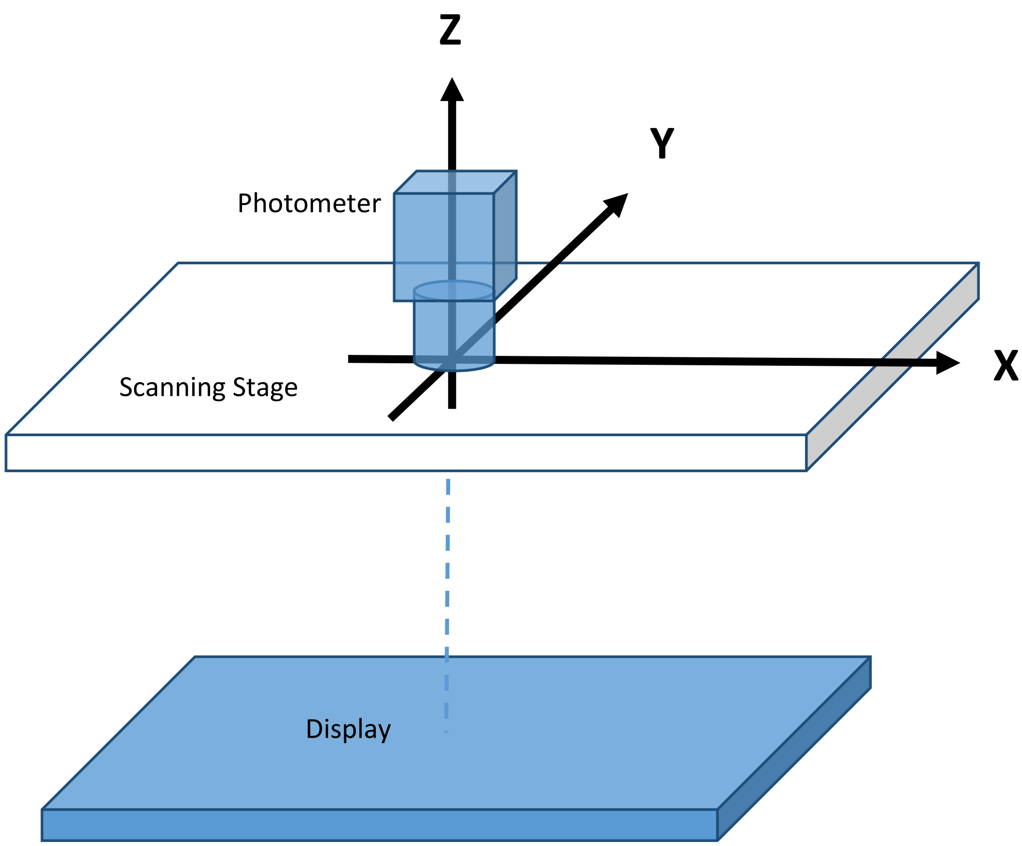

Figure 26. Coordinate System

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8.2 Testing Steps

As detailed in the test specifications above, we will need to follow the following steps with the testing. The system has to supply the tools for these steps>

8.2.1 Alignment. The alignment process is done with a cross hair drawn on the display, and the camera or photometer is moved to be centered with the cross hair. Once done, coordinate systems of the motor controllers are zeroed to have (x, y) = (0, 0). Any motion is listed relative to this point. The system should allow manual motion for this alignment process, and zero set.

8.2.2 Visual Inspection. The visual inspection was described in Section 7.7 in detail. Please review it. It starts with full primary colors screens, and gray levels, continue with grid lines, checkerboard, and finally 3D patterns or movie.

From system point of view we need:
(1) A set of patterns and images residing in the display computer
(2) Ability to control these images from the main control computer
(3) Motion control to move the testing equipment away and leave free viewing of the screen

At the end of the visual inspection – if all is OK we move to the "basic tests", and report in the main computer the all passed. The software should include this step. If there is any problem, the tester has to check and consult with the display manufacturer. The trouble shooting can include wires, connectors, other hardware problems, or software issues.

8.2.3 Basic Tests. We discussed the basic tests, and their procedures in Section 7.8. Table 6 summarized the measurements, their detailed procedure location and the reference IDMS1 section (e.g. IDMS1-Section 8.1, page 138). There are three groups of measurements:
1) Luminance, uniformity (including MURA), colors and contrast at normal view
2) Angular luminance, and colors over viewing angles
3) Temporal measurement – flicker, video smearing (at normal)

As described in Sections 6.8.1 to 6.8.5 there are two methods for the luminance and other normal view measurements: (1) 9 point spot measurements, and (2) area measurement with a photometric camera. In the next section we will discuss the potential equipment and the advantage of each. Similarly the angular measurements have also few options. Both categories (a) and (b) will use either a spot-photometer on a motion stage or a camera on a stage. More discussion is coming. For the temporal measurements we will use one of the commercial flicker tester in semi-manual mode.

8.2.4 Special Tests and Depth. As discussed earlier, we will have special tests including resolution and depth measurements. In Section 7 we discussed three methods of resolution and depth measurement, which mostly fit for light-field displays. For volumetric displays we propose to use methods similar to range-finding. However, most range-finders are for reflecting object. We will optimize the methods for light emitting objects, and will discuss it later in this report.

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9.0 PHOTOMETER SELECTION

The basic measurements include luminance and color measurements. We already explained the different instruments for measurements (Section 3.7), and the difference between sampled uniformity (Section 3.4.1) and area uniformity (Section 3.4.2). In Section 6 we already started to discuss photometers selection (Sections 6.3 –Photometers and 6.4 –Photometers Selections and Table 2). We explained the different types of photometers, and their advantages and disadvantages. Table 8 is a summary of the types. The ones that are highlighted should be considered for our project.

Table 8. Type of Photometers for Luminance and Color Measurements

LUMINANCE	COLOR
Spot-photometer – with focusing optics (view typical 1° ~ 2°)	**Spot-photometer – with focusing optics and color filters (View 1° ~ 2°)**
Spectra-spot-photometer – with focusing	**Spectra-spot-photometer – with focusing**
Contact luminance meter (pack)	**Contact luminance meter (pack) with color filters**
Luminance meter (Lux-meter)	
Camera (e.g. CCD)	**Camera (e.g. CCD) w. Colors**
Temporal luminance sensor – for response time and flicker tests	

For most luminance and color measurements we would like to use the Photometric camera. It gives small and large area uniformity and eliminates the need for mechanical scanning, which is time consuming. However, we need to verify that the camera has the minimum resolution for the specific display. Also the camera has enough dynamic range (0.1 cd/m2 – to 4000 cd/m2). This is needed to cover bright luminance displays, and to measure black screen in dark environment (< 0.1 cd/m^2). Using the camera for color measurement require proper accuracy. It should have an error vector smaller than Ruv = 0.003 in the CIE-1976 (u', v') color space.

Further to the explanations in Section 7.0, we can summarize these needs as:

1) **Considerations for spot-photometer**
   a) Spot measurement at the center, with low luminance of 0.1 cd/m^2 (or smaller).
      - The reason is to allow CR of 1000:1 for a display with 100 cd/m2 full screen white. This makes black luminance of 100-cd/m^2 / 1000 = 0.1 cd/m^2.
   b) The optics of the spot-photometer should accommodate displays with images that are away from the physical surface of the display
   c) The spectra-spot-photometer should have color accuracy of Ruv = 0.003 (or smaller).
      - Ruv – is a vector change in the CIE-1976 (u'-v') color space

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2) **Considerations for photometric color camera**
   a) Low luminance reading = 0.1 cd/m2 (or smaller)
   b) Color accuracy - Ruv = 0.003
   c) The optics can fit the depth range of typical displays
   d) The software can support small and large area uniformity calculations, both for luminance and colors. For instance, the Radiant model: ProMetric / IC-PMG3 (or other ProMetric models), can do this.

In case that the photometric camera has the features needed, we prefer to use it.

3) **Considerations for temporal measurements**

For temporal measurements we will need:

   (a) A fast response sensor
   (b) Interface electronics (pre-amplifier)
   (c) Oscilloscope

There are commercially available sensors system (e.g. Westar / TR-200) that includes the sensor with a lens, pre-amplifier and hardware to input the signals into a computer. The signal analysis is done in the computer.

4) **Our main debates**

Our main debate is the angular measurement with the camera. When focusing with the camera on a surface at an angle the edges will be out of focus. However, if the view distance is long enough, the de-focusing will be minimal.

The IDMS1 recommends to have the camera at a distance of = 2570 x pixels pitch. For a display with 1 mm pixel pitch, this will make ➔ L = 2570 * 1 = 2570 mm = 2.57 m. This is a very long focal length. That will be good for angular measurements, but will be difficult for having the proper magnification to fill the display screen into the whole CCD array.

We will come back to this topic. In the meantime let's review the potential photometers and cameras that could fit.

9.1 Spot-Photometers

9.1.1 The Spot-Photometers Types. The spot-photometers are separated to two types:

(a) Single detector and color filters on a rotating wheel.
   1. Photomultiplier detectors are mostly used.
   2. Cooled silicon photodetectors are sometimes used
   3. The color filters together with the photo-detector spectral behavior, match the CIE Tristimulus curves

(b) Spectra-spot-photometers with an array of sensors and grating to separate wavelength, to measure a full spectra.
   1. Sometimes the sensors array is cooled to get a better signal to noise (S/N) ratio

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2. The photometers usually use the range of 380 nm to 780 nm, and have steps of-
3. Steps are either 4 nm, 2 nm, or 1 nm.
4. Smaller steps give better accuracy for color calculation, and sometimes better sensitivity. However, photometers with 4 nm are adequate as long as their S/N is high enough.

9.1.2 Our Considerations.

(a) We would like to have a spectra-spot-photometer that has low enough sensitivity for dark levels. The specs that we are looking for are:
1. Viewing angle of ½º , 1º, or 2º
2. Lens for viewing of distances of 5 cm to 200 cm (2" to 80")
3. Lens can be changed depending on application, however, a zoom lens is preferred
4. Low luminance level of < 0.1 cd/m2
5. Luminance accuracy of 4% or better
6. High luminance of 4000 cd/m2 (it will be OK to use neutral density filters on the lens)
7. Color accuracy of 0.003 (in the CIE-1976-u'v' space) and repeatability of σ_{col} < 0.002.

9.1.3 Review of few potential spot-photometers.

(a) Manufacturer: Photo-Research: Spot-photometer model: PR-880 –

- Is a photomultiplier based photometer.
- It has several viewing angle options (1/8º, ¼º, ½º, 1º and 3º).
- It has color filters, which specs are ±0.015 vector in the CIE-1931 (x-y) space
- It has ample dynamic range (lowest is 3×10^{-4} cd/m^2)
- Using the ND filter on the high end it is practically limitless.
- The display interface is RS-232 and gives enough flexibility to write dedicated routines

A photo of the PR-880 copied from the web page is in Figure 27.

URL: http://www.photoresearch.com/current/docs/880%20brochure.pdf

(b) Manufacturer: Topcon: Spot-photometer model: BM-7A –

- Is a photomultiplier based photometer.
- It has several viewing angle options (0.1º, 0.2º, 1º and 2º).
- It has color filters, which specs are ±0.002 vector in the CIE-1931 (x-y) space
- It has ample dynamic range (lowest is 1×10^{-2} cd/m^2)
- Using the ND filter on the high end it is practically limitless.
- The display interface is RS-232 or USB-1.1 and gives enough flexibility to write dedicated routines

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A photo of the BM-7A copied from the Westar web page is in Figure 28.

URL: http://www.westardisplaytechnologies.com/wp-content/uploads/Topcon-BM-7A-Brochure.pdf

Figure 27. Photometer / Colorimeter – Photo-Research PR-880

Figure 28. Topcon BM-7A Luminance Colorimeter

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(c) Manufacturer: Minolta: Spot-photometer model: CS-100 –

- Is a x3 silicon based photometer with fixed filters.
- It has a fix viewing angle (1º).
- The color accuracy is ±0.004 vector in the CIE-1931 (x-y) space
- It has ample dynamic range (lowest is $1x10^{-2}$ cd/m^2)
- The upper luminance is 299000 cd/m^2
- The luminance accuracy is ±2% of the reading
- The interface is RS-232C.

A photo of the CS-100 copied from the web page is in Figure 29.

URL: http://sensing.konicaminolta.us/applications/light-measurement/

Figure 29. Minolta CS-100 Luminance and Color Meter

Since we would like to use spectra-spot photometer in case they meet the criteria of minimum luminance of 0.1 cd/m^2, we bring the above examples mostly for reference.

9.1.4 Review of Few Potential Spectra-Spot-Photometers. These photometers have more color accuracy and long term stability. Some of them lack in low luminance sensitivity.
One example is the Photo-Research PR-655, which can go as low as 0.7 cd/m2. This might not be sufficient for high contrast displays. For reference, Figure 30 shows the PR-655 photo.

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Figure 30. Spectra-Spot-Photometer - Photo-Research PR-655

We would like to consider the PR-670. This spectra spot photometer has double the number of sensors (256) compared to the PR-655 (128 sensors). It will read luminance as low as 0.03 cd/m2, which will be fine for our purpose. Figure 31 shows a photo of the PR-670.

One other feature that makes the spectra-spot-photometer advantageous over the spot photometer, is faster measurement time.

Typical features of the PR-670

- Spectra reading with 256 sensors
- Several view angles adjusted automatically (1/8º, ¼º, ½º, and 1º).
- The color accuracy is ±0.0015 vector in the CIE-1931 (x-y) space
- It has ample dynamic range (lowest is $3x10^{-2}$ cd/m^2)
- The upper luminance is 8,566,000 cd/m^2
- The luminance accuracy is ±2% of the reading
- The interface is RS-232, USB, and optional blue-tooth.

URL: http://www.photoresearch.com/current/docs/PR-6%20Series%20%20Brochure.pdf

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Figure 31. Spectra-Spot-Photometer - Photo-Research PR-670

Similar spectra-spot-photometer is – Minolta – CS-2000A

Figure 32 is showing the CS-2000a spectra-spot-photometer.

Figure 32. Spectra Spot Photometer - Minolta CS-2000A

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Some of the CS-2000A features:

- Spectra reading with probably 256 sensors
- Several view angles selectable by application (0.1º, 0.2º, and 1º).
- The color accuracy is ±0.00? vector in the CIE-1931 (x-y) space
- It has ample dynamic range (lowest is 3×10^{-3} cd/m^2)
- The upper luminance is 1×10^{6} cd/m^2
- The luminance accuracy is ±2% of the reading
- The interface is RS-232.
- Claimed 5 sec per reading.

URL:
http://www.konicaminolta.com/instruments/download/catalog/display/pdf/cs2000_catalog_eng.pdf

9.1.5 Making Decision on Type of Photometer or Camera for Uniformity and Color Tests.

The selection of photometers for our purpose is not an easy task. In order to make a decision, we put the following chart, in Figure 33.

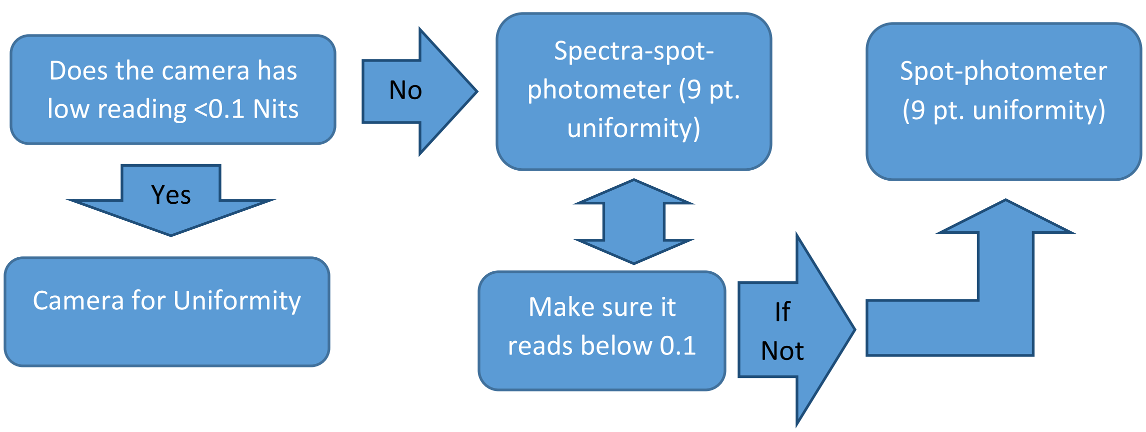

Figure 33. Uniformity and Color Decision Making

Here are some of the considerations:

The photometric camera is the easiest way to measure the luminance uniformity, the colors and their uniformity, and the contrast over the area. It also identify local non-uniformity like blemishes (called in the literature MURA). The only must condition is that the camera has low luminance sensitivity of 0.1 cd/m2 or below. This condition is needed to account for high contrast displays, where the black screen levels are low. Since we identified photometric cameras that fulfill this condition, we will use them for uniformity and color tests

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9.1.6 Review of Potential Color Photometric Cameras. The selection of cameras is influenced by few features:

(a) Resolution –
  i. It should be minimum x3 times the pixels pitch, and preferably x10 times or higher.

(b) Focal distance –
  i. Depending on the optics (lens selection)
  ii. As mentioned, we would like to comply with the IDMS1 recommendation of view distance = 2570 x pixel-pitch. This might not be practical in some cases.

(c) Sensitivity and Dynamic range –
  i. Lower limit luminance below 0.1 cd/m^2 - (to meet black levels of high contrast displays)
  ii. High luminance of at least 4000 cd/m^2 – (to meet bright displays full screen white)
  iii. The dynamic range is 40,000:1

(d) Luminance accuracy of ±3%

(e) Color accuracy of less than = 0.003 Ruv (in the CIE-1976 space, u'-v')

9.1.7 The following cameras are potential candidates for our testing system - Table 9 Summarizes the Potential Color Photometric Cameras that are within the above §9.1.6 requirement, or close.

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Table 9. Color Photometric Cameras - List of Companies and Models

Manufacturer	Camera type	Model(s)	comments
Radiant-Zemax	ProMetric	IC-PMG-3	6.3 M (has MURA testing); 14 bits
Radiant-Zemax	ProMetric	IC-PMI-8	8.1 M; 12 bits; min=0.0005 Nits
Radiant-Zemax	ProMetric	IC-PMI-16	16 M; 12 bits
Radiant-Zemax	ProMetric	IC-PMI-2	1.9 M
Radiant-Zemax	ProMetric	IC-PMG-2	1.6 M; 14 bits;
Instrument-Systems	LumiCam	LumiCam 1300 color	1.2 M; 12 Bits;
Instrument-Systems	LumiCam	LumiCam 1300 advanced	1.2 M; 12 Bits;
Photo Research	DVP-Digital Video Photometer	PR-920	1.0 M; Nice selection of lenses; min=0.03 Nits; 16 bits
Westboro Photonics	Imaging Colorimeter	WP-640	4 M; 12 bits; Min=0.1 Nits
Westboro Photonics	Imaging Colorimeter	WP-690	9 M; 12 bits; Min=0.1 Nits
Westboro Photonics	Imaging spectral Colorimeter	WP-214	0.5 M (380-780nm spectral)
Konica Minolta	2D Color Analyzer	CA-2500	1 M (MURA testing, 3 lenses: S, W-wide, T-telephoto, allows 2m distance, colors 0.005 vector)

Figures 34, 35, 36 and 37 show photos of the cameras (see next page).

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Figure 34. Photometric Camera - Radiant ProMetric IC-PMI Series (Color)

Figure 35. Photometric Camera - Instrument-Systems Model LumiCam 1300 Color

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Figure 36. Photometric Camera - Photo Research - Digital Video Photometer - PR-920

Figure 37. Photometric Camera - Konica Minolta - 2D Color Analyzer - CA-2500

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Additional information from the search:

These companies did not have photometric cameras

- Autronic-Melchers
- Gamma-Scientific
- Gooch and Housego
- Gretag Macbeth / X-Rite

Companies with monochrome (no color) photometric cameras

- Microvision (CCD camera – SS-410-XE, 1.4 M) www.microvsn.com
- Tricore-Systems (823 Firewire Video/Imaging Photometer; 10 bits, low resolution) – http://www.tricor-systems.com/products/light_measurement.htm

9.1.8 References for the Color Photometric Cameras. - Following are several web locations with information that might be useful:

(1) Comparison table of Radiant Zemax (Now: Radiant Vision Systems) cameras is here: http://www.radiantvisionsystems.com/sites/default/files/library-documents/Learn.SpecSheet.RVS%20ProMetric%20Comparison%20Chart%2011by17%20BNM%20format%2020141219.pdf

(2) LumiCam brochure is here: http://www.instrumentsystems.com/fileadmin/editors/downloads/Products/LumiCam_1300e.pdf

(3) The Photo Research brochure: http://www.photoresearch.com/current/docs/920.pdf

(4) Westboro cameras: http://www.wphotonics.com/colorimeters.php
NOTE: Viewing Angle (Westboro): To measure luminance and chromaticity as a function of viewing angle, the WP214 can be combined with a CONOMETER® lens.

(5) Konica Minolta – 2D color analyzer:
(a) Brochure: http://www.konicaminolta.com/instruments/download/catalog/display/pdf/ca2500catalogeng.pdf

(b) Manual: http://www.konicaminolta.com/instruments/download/instruction_manual/display/pdf/ca-2500_instruction_eng.pdf

9.1.9 Recommended sequence of measurements. - This section was discussed in §7.8.6, including table 4, and is repeated here for reference.

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So far we covered several measurements, some of which can be done together, like luminance, colors and contrast ratio uniformity. In this section we would like to recommend of optimal sequence of measurements. Table 10 lists the measurements that can be combined, and then do calculations and reporting in a raw. It uses short notations as used in previous sections.

Table 10. Optimal Sequence of Measurements

Available equipment	Measure	Calculate	Report
Spectra-spot-photometer	9 points: Lum, U'V' – Full screen - W,K,R,G,B	Lum, *Δu'v'*, Cu(W/K) – Non-uniformity	Center: Lum(W); CR Non-Unif: Lum, *Δu'v'*, Cu
High Resolution mono-camera	Full screen (Lum.): W,K, S127, G20%,G05% (gray)	Contrast (Cu=Lw/Lk); Non-unif. W, Cu, Gray	Non-unif. W, Cu, Gray Maps: W, Cu MURA
Color camera	Full screen (Lum, U'V'): W,K,R,G,B, S127, G20%, G05% (Gray)	Contrast (Cu=Lw/Lk); Non-unif. W, Cu, Gray *Δu'v'*-for R,G,B	Non-unif. W, Cu, Gray Maps: W, Cu MURA Differ.- *Δu'v'* for RGB Color maps

Conditions:

(1) Available: Spot-photometer + Mono Camera
  a. Do all listed measurements (for both)

(2) Available: Spot-photometer + Color Camera
  a. Do only center point with spot-photometer, and all other listed measurements

9.1.10 Deciding which photometer or camera fits angular measurement. We already mentioned that photometric cameras are more efficient for uniformity and colors. They are faster and give more information, including local non-uniformity (and MURA). However, there is one problem when using them at an angle. The edges of the display along the tilt orientation will be out of focus. One side is closer, and the other too far. If this problem is not resolved, we will have to use a combination of camera for normal view aerial tests, and a goniometer with a spot-photometer for angular measurements at the center of the display.

The decisions to be made are summarized in the chart in Figure 38.

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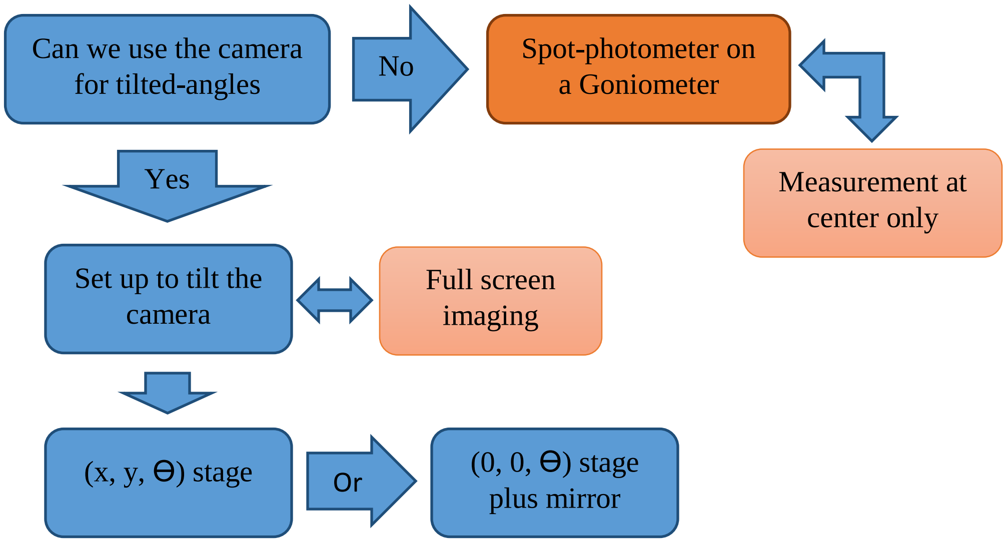

Figure 38. Angular Measurements - Decision Making

Therefore, we should look into methods that will allow using the camera at angles of at least ±30º away from normal view.
The camera will allow us to see the full screen image at an angle, including local non-uniformity. The spot photometer on a goniometer will give only center of display angular change in luminance and colors.

9.1.11 Focusing calculations for a tilted camera looking on the display at an oblique angle.
In Figure 39 we have a schematic of the situation. The camera is mounted on a scanning stage that can move left / right. Let us assume that this is along the X-axis (see figure 29 –for notation). Let us also allow the camera to tilt with a controlled rotating fixture. The tilt angle will be Theta (ϴ) and we would like it to have at least 30º tilt on each side. In Figure 16 we have the motion in the positive X -direction and the tilt is negative ϴ.

Using the notation of Figure 29, we see that L – is the camera lens distance from the center of the displays, in normal view direction. Once we move the camera distance X in the positive direction, and tilt it to focus on the center on the display, then the distance between the camera and the center is M. In this position, the camera distance to the edges of the display is P and Q respectively. The display width is W.

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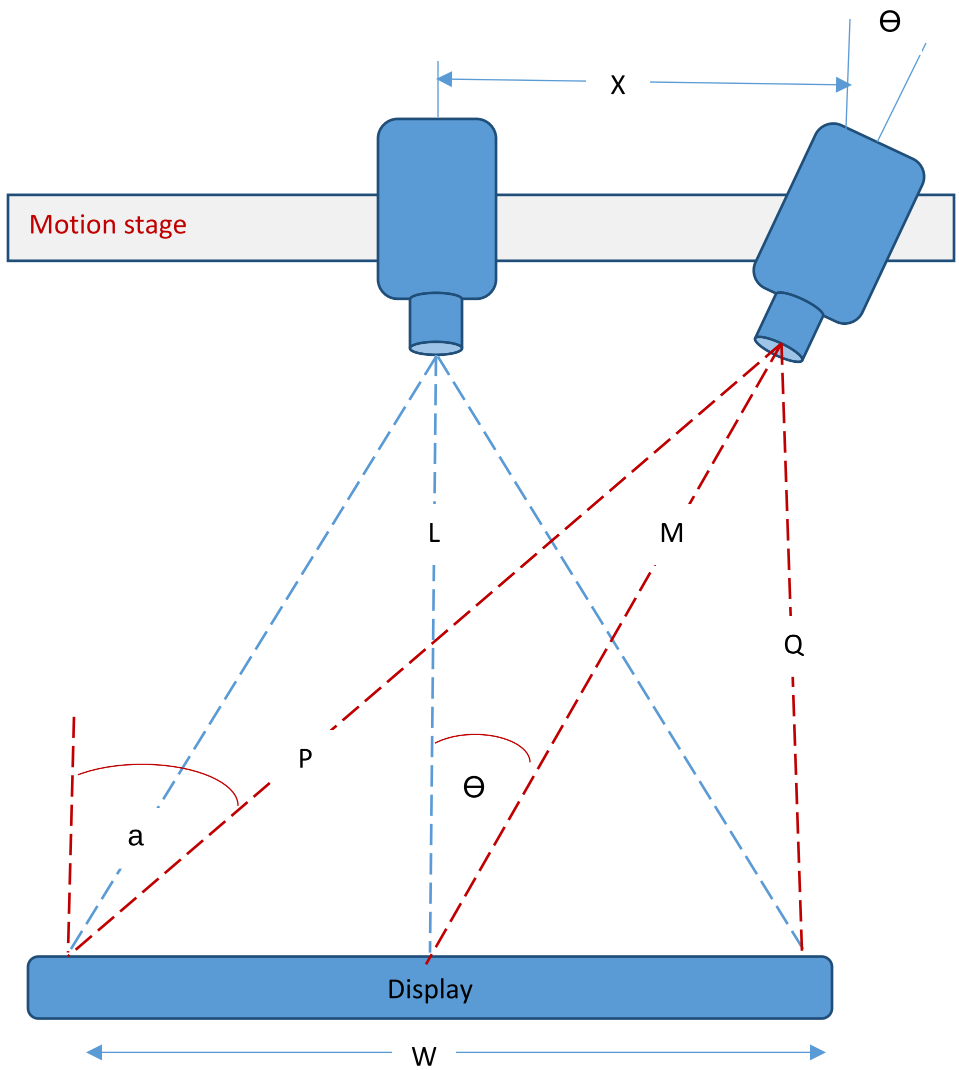

Figure 39. Focusing of a Camera at Tilt Angle

Using these notations we see that:

Equation 7 - $X = L*TAN(\Theta) \rightarrow \Theta = ATAN(X/L)$

Equation 8 - $L^2 + (X + W/2)^2 = P^2 \rightarrow P = sqrt(L^2 + (X + W/2)^2)$

Equation 9 - $P = sqrt(L^2 + (X + W/2)^2)$

Equation 10 - $Q = sqrt(L^2 + (X - W/2)^2)$

A table with calculations for several X value in steps of 100 mm was built to see the difference between L and M and also the difference between P, Q and M. Figure 40 shows the values of M, P, and Q for several X value, as a function of tilt angle ϴ. This chart is for L = 1000 mm (1 m.). A similar calculation was done for 2 m. distance, and is shown in Figure 41.

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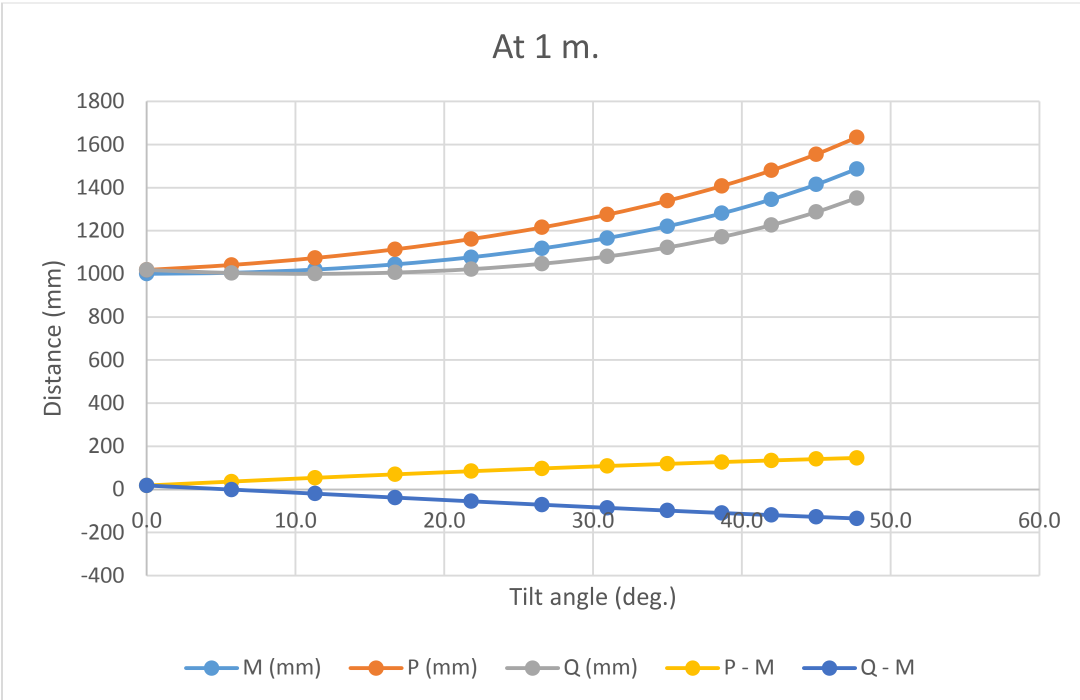

Figure 40. Tilt Angle Camera View - Values of Distance to the Center (M) and Edges of the Display (P, Q) for Several View Angles (Tilt angle). Camera is 1 Meter Away.

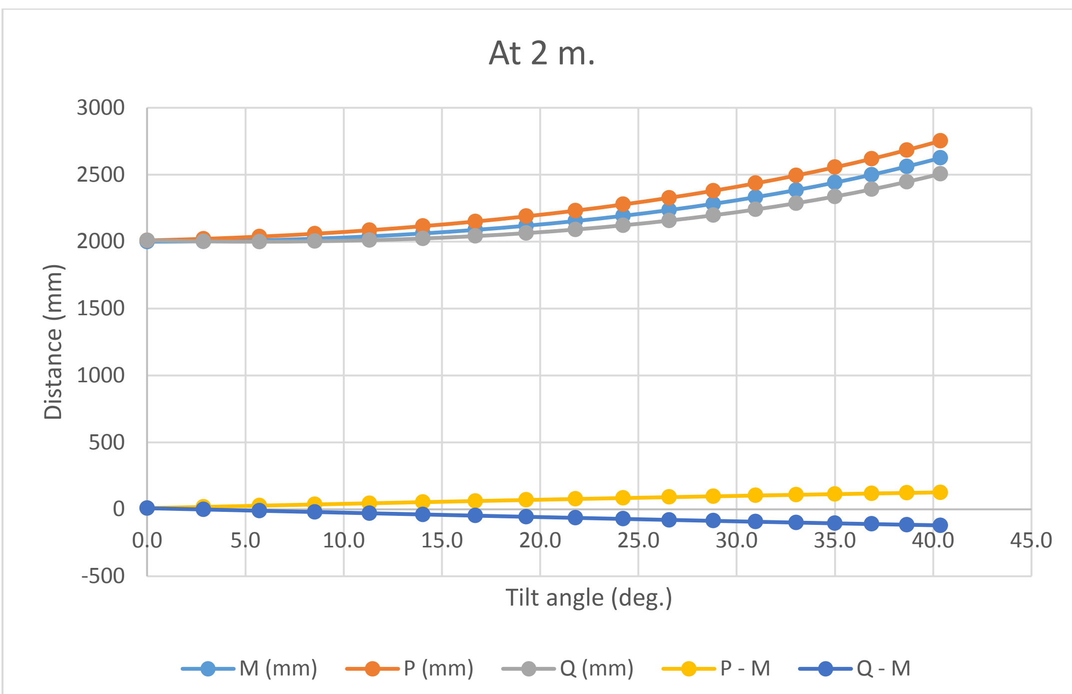

Figure 41. Tilt Angle Camera View - Values of Distance to the Center (M) and Edges of the Display (P, Q) for Several View Angles (Tilt Angle). Camera is 2 meters Away.

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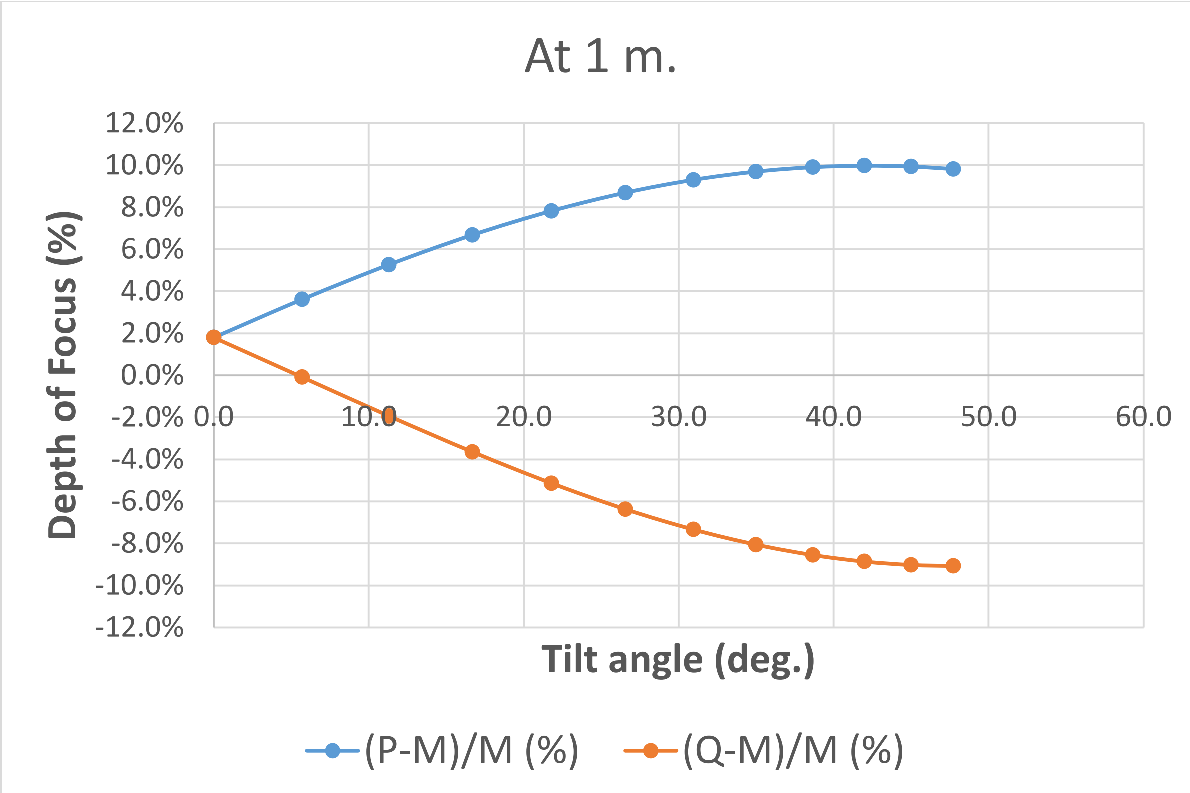

Figure 42. Depth of Focus (in Percentage) at 1 m. Distance

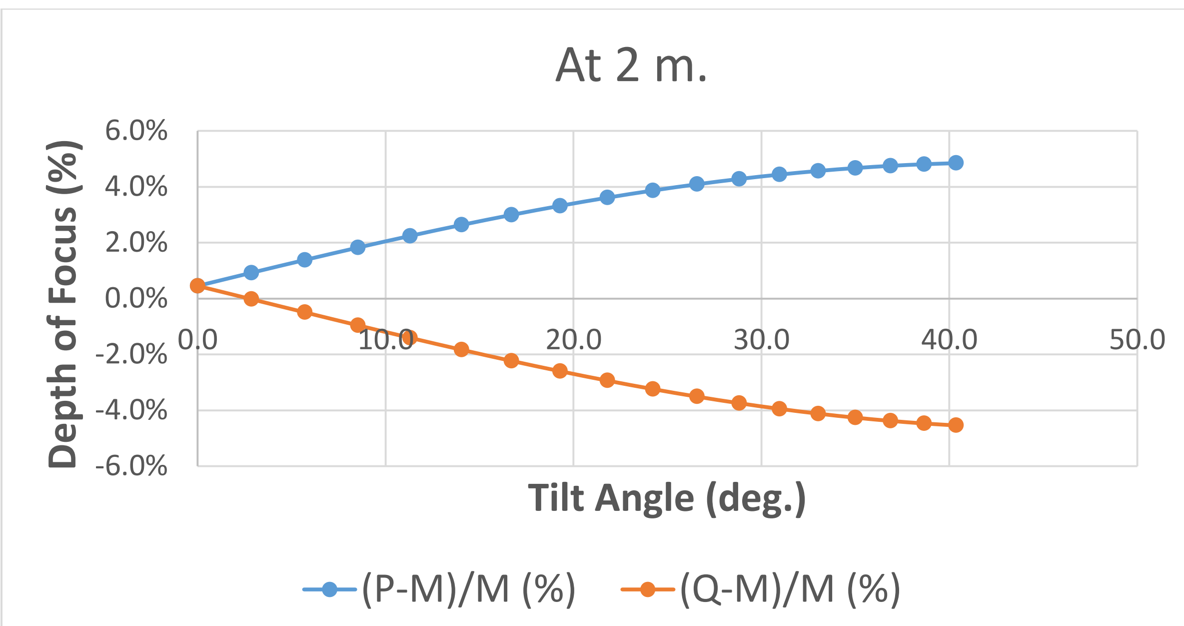

Figure 43. Depth of Focus (in Percentage) at 1 m. Distance

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As we see, increasing the camera view distance (e.g. from 1 m. to 2 m.) is reducing the relative difference between the camera distance to the center, and the edges. This might bring it to the lenses specs of focal depth.

In case we will need to fold the optics for long view distance, we might consider to fold the optics with a mirror. A schematic for this concept is shown in Figure 44.

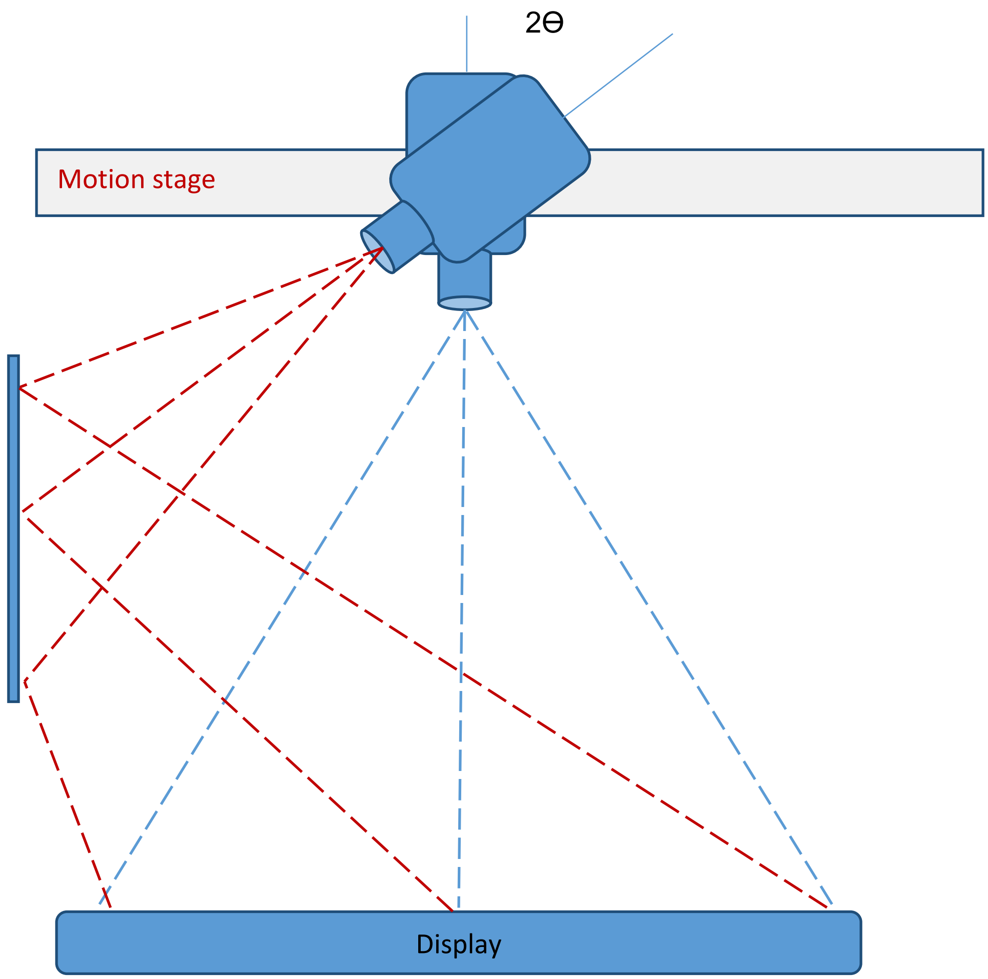

Figure 44. Folded Optics for the Camera View

Considerations:

- The focal lens through the mirror is increased
- The relative distance between center and edges is maintained about the same
- The only advantage is that there is no need to move the camera in X direction.
- Motion needed: Only tilting the camera

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9.1.12 Checking with Vendors about Focal Length and Depth of Camera Lenses. A discussion with Radiant Zemax (now Radiant Vision Systems), indicated that with proper selection of lens of focal distance, the display can be measured at an angle. This will be defined by the depth of focus of the combination. Some propriety number that they shared with us are summarized in Table 11 at the Appendix A (limited access).

If this will not be sufficient, they have the flexibility of testing the image as two different focal distances and analyze the images accordingly. This will accommodate the fact that one edge of the display is closer than the center, and the other edge is further away. The lenses and sensors uniformity are calibrated at normal view, and should maintain the calibration during a tilt angle test.

As we can see, the focal depth is fairly small, and we have to consider if angular measurements with the camera will work OK. As shown in Figure 42 and 43 we need more depth for the edges of the display.

Options to overcome these problems are:

(a) Take dual images at two focal distances, or more than two captures.

(b) Inspect only small section of the display at a time, and then move the camera to other sides of the display. In this case we will use higher magnification.

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10.0 SYSTEM STRUCTURE

The test system will include:

(a) Photometer / camera - discussed in the previous section
(b) Motion system - to position the photometer
(c) Pattern generator - to present images on the tested display, and
(d) A computer to control and accumulate data.

Figure 45 shows a schematic of the test system.

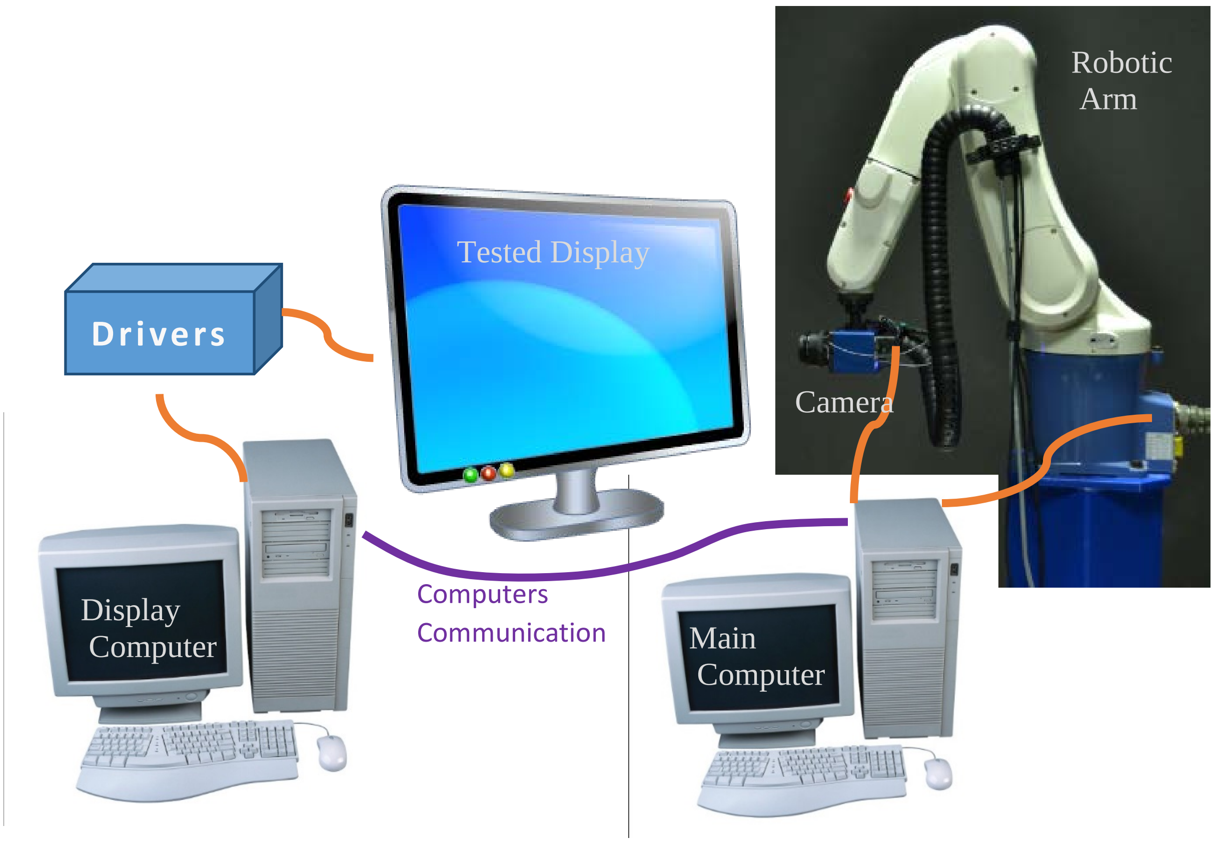

Figure 45. Schematic of the System Structure

So far we discussed in details the photometers or photometric camera part of the system. We assume that the display vendors will support us in communication to their system, and presentation of the patterns listed earlier. We will need to agree on the communication protocol, and the language to bring on the screen each of the patterns.

In the following section we will discuss potential optical stages, or robotic arm system. The main computer should be adequate to communicate to the mechanical stages, or to the robotic arm, and control it. The computer also should “talk” to the camera (or photometer) – both

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operation commands and data collection. This will be supported by the camera manufacturer software.

The data will be accumulated on the main computer and will be also processed to have the proper presentation for a final report. It will include a fail / pass criteria. It will also accumulate the data into a comparison table.

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11.0 MECHANICAL STAGES / ROBOTIC ARM

Commercial testing systems today are using mechanical stages, with controlled motorized systems. The stages are either mounted on each other, or split between the photometer and the tested display. For example, the photometer is mounted on a translation X, Y, and Z stages, while the display is mounted on a rotation stage (tilt, or both tilt and yaw).

Figure 46 shows an example of such a test system, made by Westar Systems. The two photometers are mounted on the X-Y-Z stage (translations), while the display is on a rotating stage θ-φ (tilt and yaw).

Figure 46. Example of Existing Test System - Westar / FPM-510

More advanced system by Westar and other companies use the basic concept of separation of stages to both the photometer and the display.

Here are some companies that have commercial testing systems:

(1) Westar System (http://www.westardisplaytechnologies.com)
(2) Autronic-Melchers (www.autronic-melchers.com)
(3) Micro Vision, Display Measurement Systems (http://www.microvsn.com/)

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This list does not include stand-alone systems like the conoscopic system of Eldim which measures angular behavior at a “glance”.

Westar has a 5-axis measurement system (FPM Series F) to accommodate for angular measurements of large size panels. It has a fiber optics photometer with a gimbal on the stage. This could fit for our project, except that some of the displays that we will test are in horizontal (table top) format and this system will not be able to test them. We might consider adding a long arm and mounting the photometers on it. It should be fairly cumbersome.

Both Microvision and Autronic have test systems that can be modified, with goniometer as needed. However, both modifications are significant.

Figure 47 shows a Microvision Systems positioning stage (X-Y, model SS30) with a goniometer option (model: SS420) mounted as the photometer. The Goniometer is meant to measure at close proximity to the display surface.

Figure 47. Microvision Measurement System, Including X-Y Positioner and Goniometer

11.1 Limitations for our Test System

Our system has some limitations as far as the mechanical stages. Here is a summary:
(a) The photometer (or camera) cannot be too close to the display surface, since sometimes the image is above or below the physical surface of the display.

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(b) The display system is sometimes heavy and big, and therefore cannot be mounted on any motion stage. This means that the photometer should be mounted with all the degree of motions needed.
(c) Some of our displays are vertical, and be measured from the front, and some are horizontal (table top) and should be measured from above. The scanning system and stages should allow both options. An extended arm to modify from one case to the other is allowed.

With these limitations in mind one could think of a robotic arm as an option. Today robots are fairly advanced and have flexibility and easy controls. One such robot is sold by Gamma-Scientific and is discussed below.

11.2 Robotic Arm

The use of a robotic arm to make all the measurements is matching our limitations above. We just need to find a robotic system that has the needed degrees of motion freedom, and can carry the weight of the photometer or combination of photometer and camera(s).

Gamma-Scientific – has a 6 axis robotic arm that can be used with either their spectra-spot-photometer, or maybe can be used with our choice of camera, and photometer. Figure 48 is showing this robotic system, targeted for display testing.

Figure 48. Robotic Arm - Used for Display Testing - Gamma Scientific Test System

This robotic system was developed with curved large size TV display in mind. The view distance in this example complies with our needs. Further information about this robotic system is in the web page: http://www.gamma-sci.com/wp-content/uploads/2011/10/Robotic-Display-Measurement-System-Data-Sheet-Gamma-Scientific.pdf

We consider to use this robot, but with a different camera that will have enough resolution and color capability. That will mean that we will design special mechanical adaptors at the tip of the arm.

11.3 Basic Measurements Summary

So far we described the testing system, the photometers, the stages / robot, and the patterns. This part of the testing system will do the basic measurements listed in Table 6.

Since we are still negotiating with vendors about their photometers and photometric cameras about specifications, we don't have a definite system design.

However, based on the information that we have now, we might construct a system that has a Radiant 8 MPixel camera (model: IC-PMI-8) mounted on a Robot by Gamma-Scientific, or on a similar robot.

At the moment the robotic system is sold by Gamma-Scientific with their spectra-spot-photometer and we will have to negotiate about the possibility of buying the robot part of it, and add the camera. Alternatively, we can leave the spectra-spot-photometer and add the camera to this system.

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12.0 DEPTH MEASUREMENTS

In Section 7.0 - 3D Depth New Methods, we discussed the three options for depth measurements:

(a) Visual Assessment –
   a. Using a dual depth checkerboard, and/or
   b. The hedgehog rotating pattern proposed by the ICDM1 [1].

(b) Computed patterns (Lee's method) [24] –
   a. Put triangle in one depth level, and square in another level and report if one or both are in focus (clear).
   b. The depth of the triangle and square are defined by Computing Integral Imaging Reconstruction (CIIR)

(c) Depth resolution measurement –
   a. This is the method described at IDMS1 [1]
   b. It needs Sinusoidal patterns (horizontal, vertical or diagonal)
   c. A very high resolution camera (x10 times the pixels pitch)
   d. We measure the optical MTF for the Sinusoidal patterns as several depth
   e. Then convert the horizontal MTF to depth after dimension calibration

The details of these methods are in that Section 8.0 - Test System Configuration.

All these measurements are focused on Light-Field displays. Since our project needs to support also holographic and volumetric displays, we will discuss here additional method for these applications.

12.1 Depth Measurements Using Range-Finding Technique

Photography cameras are using range-finder technique to find the focal depth and adjust the lens to best focal distance. There are three methods to do that:

Manual Methods

(a) Dual view and triangulation (or moving a beam splitter to coincide two images)
In the manual method, the image is viewed through two separated lenses, with slightly different viewing angle. The images in the eye-piece are moved by a beam-combiner until manually are coincide. The rotation of the beam-combiner is indication of the distance.

Auto-Focus Methods

(b) Phase detection
In the phase detection method, the image of a sharp object is viewed through two separated lenses and two sensors array. The center of each of the sensors image is recorded, and feedback to the main lens to adjust. When both centers of the images are overlapping the lens is in optimal focus.

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(c) Contrast Detection

In the contrast detection method, the image contrast is monitored to have maximum separated peaks in the Fourier frequency domain. The lens is moving until the contrast is optimum.

In our case we have a display which is emitting light. We would like to automate method (b). The method is described schematically in Figure 49.

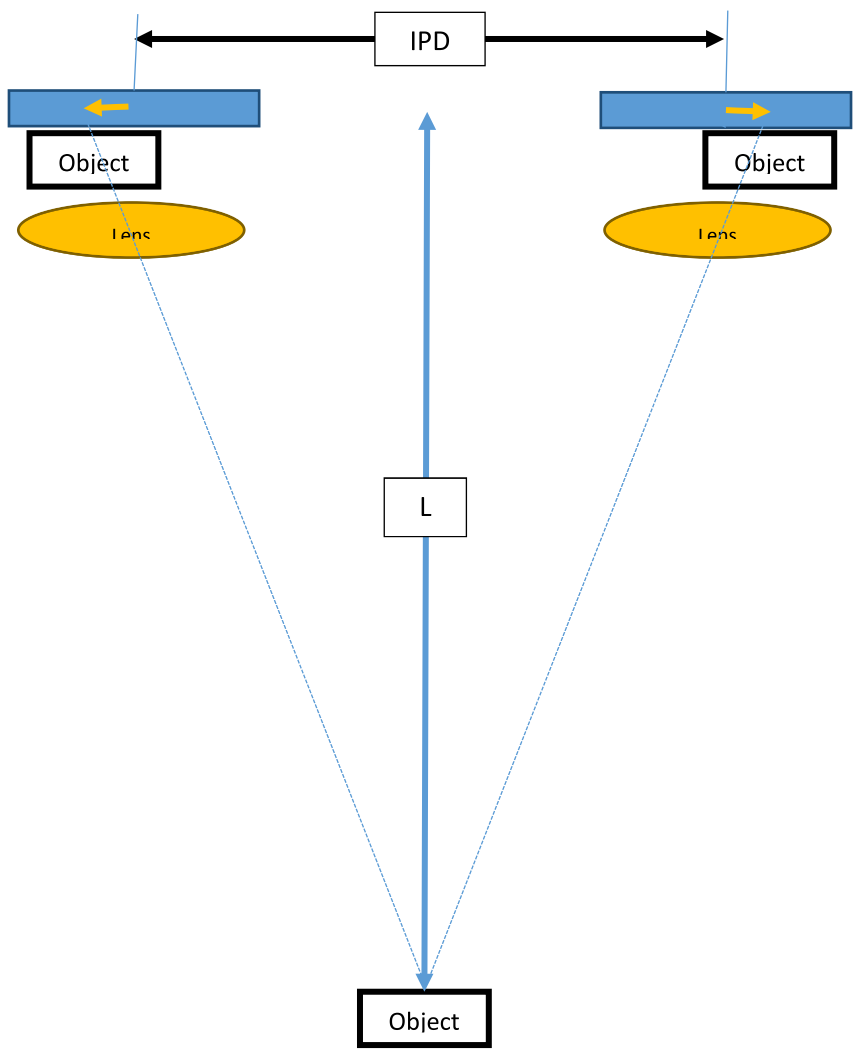

Figure 49. Concept of Range Finder Used for Depth Measurement

The measurement will need the volumetric display to present a line as a defined depth. This line (the object) will be viewed through two separated lenses. The object image is viewed by a sensor array behind each of the lenses, and will appear shifted from the center by a distance X. The shift will be in opposite directions in the lenses. Using basic geometry we see that:

Equation 11 - $X / F = ½ *(IPD) / L$

Where: X – shift of the image of the object from the center of the sensor array;
F – Focal distance of the lens

IPD – Distance between the centers of the lenses
L – Distance to the object (the parameter that we are looking for)

Organizing equation 11 to solve for L we get:

Equation 12 - $L = ½ *(IPD) * F / X$

Since X of right and left sides might be slightly different, we can re-write equation 12 for:

Equation 13 - $\boldsymbol{L = (IPD) * F / (X_R + X_L)}$

Where: X_R, X_L – are the shifts for the right, left sides respectively

To implement this concept we can use either a self-built system as described above, or modify a commercial unit.

The other idea is to use the photometric camera and the motion control to read the left and right positions one at a time. In this case we can separate the locations (IPD) further away and increase the accuracy of the measurement.

To measure the depth sensitivity, we should repeat the depth measurement for few depths and see how close we could we separate the readings.

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13.0 CONCLUSIONS AND RECOMMENDATIONS

13.1 Conclusions

We reviewed the literature and potential commercial measurement systems. We see that the field of light displays (FoLD) has to be tested first as a regular display at one or more depth values. The standard-for testing displays, which we refer to is the IDMS1 [1] covers most of the tests needed to characterize the displays. In this report we propose a set of proper tests based on the IDMS1 document and added explanations and procedures which fit better the FoLD cases.

For depth measurements we adopt one of the methods described in the IDMS1 that fits well for lightfield displays. We also recommend the visual inspection of 3D images and the Lee [14] method. For other types of displays, like holographic and volumetric, we proposed to use depth measurements based on dual cameras triangulation, similar to distance measurements used in photographic cameras. This is a proposed method, but has to be further investigated.

We reviewed different types of photometers and photometric-cameras. The values of each were weighted. We propose to use a high resolution photometric camera, since it gives more information "at a glance" and recent equipment has enough low level sensitivity and accuracy, including color measurements. There is also an advantage in software and image processing.

All equipment has to be positioned and moved in front and around the displays. We reviewed motion stages and included the new concept of using robotic arm for the measurement system. We see a great advantage to the robotic arm. It gives flexibility to go around the different types of FoLD displays. It can measure both front and top orientations. The arm can carry a camera and if needed additional photometer, as long as the weight is not exceeding the limit.

Our conclusion is that the measurement system should include a high resolution camera (e.g. 16 MPixel), with color capability. The high resolution is needed for the depth test in the IDMS1 method. Less resolution is needed for the color measurements. Mounting the camera on a robotic arm that can carry its weight (and maybe additional equipment in the future) and accurately position it around the display will be a great combination. The arm movement should be long enough (e.g. 1 m.) to accommodate different scenarios and display types. The system includes software that gives motion control to position the camera, camera controls and capture images, and image analysis and processing.

13.2 Recommendations

As mentioned, we recommend using a combination of a photometric camera mounted on an arm of a robot. This gives most flexibility to move around the different types of FoLD displays. Based on our review and analysis, the combination will include:

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a) Photometric camera –
   i) Resolution of 50% of the pixels for luminance and color uniformity
   ii) Resolution for depth measurement should be ~1/10 of the pixels
   iii) Combining both resolution requirements means 8 MPixel or 16 MPixel for most displays
   iv) Low light level sensitivity max. of 0.01-cd/m^2
   v) Color accuracy of +/-0.003 in (x, y)-CIE
   vi) Lenses to cover the different geometries of testing (e.g. 50, 100, 200 mm)
   vii) Software to control operations and download images, as well as analysis

b) Robotic arm –
   i) To carry the camera weight and potentially additional equipment (e.g. 7 kg min. and preferably 13 kg.)
   ii) Motion with enough range to cover different situations (front and top measurements). We recommend to use a 1 m. radius of motion, and 6 axis controls.
   iii) Pedestal with wheels to roll the robot close to the tested display and can be anchored to be stable during measurement.

c) Software –
   i) The system will have two software platforms:
      (1) Camera software (e.g. Radiant camera with ProMetric for control and image capture; and TrueTest with Mura for data analysis and small area uniformity)
      (2) Robotic arm software. Typically the Denso robots come with the drivers and software that control the motions and convert axis systems.
   ii) We need to integrate the two hardwares, and software systems and support it with routines to implement the recommended tests in this report.
      (1) A main computer will include the sequencing routine and the controls on the camera:
         (a) Activate a measurement of the camera with specific conditions
         (b) Capture and record the measurement data
      (2) Robot drivers – will be activated by the main computer, or by a separate computer/controller dedicated to the robot. The two options are:
         (a) The robot software resides within the main computer and cables connected to the robot control the positioning directly, or
         (b) Dedicated computer/controller of the robot receives commands from the main computer through a RS232, USB or other communication line.

d) Response time device –
   i) For the time related tests, like flicker and motion smear, we will use commercial devices as mentioned in the report Sections 3.12 and 6.8.10 above.
   ii) The device can be mounted on the robotic arm, or just put on a tripod and make this measurement separately from the full automated routine.

More details about combinations to implement the system are described in an Appendix to this report that is not published here because it contains some information that is proprietary to the vendors.

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APPENDIX A – ADDITIONAL INFORMATION

During our investigation of potential test systems and components, we gathered information which is propriety to the vendors. This includes technical information about photometric camera lenses and prices. All this information is summarized in a separate document that is not published with this report.

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